



# On/Off Axis

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# Abstract

This thesis presents an interdisciplinary investigation into sensorimotor synchronization within the context of glassblowing. The study addresses two central research questions: Can sonification of glass movement help glassblowers maintain a glass bubble on axis, and how does this differ between beginners and experts? as well as How does sonification alter human-material interaction in the hot glass workshop?

At the core of the study is a proof of concept: to address the research questions, a novel sonification tool that translates the movement of molten glass into real-time auditory feedback was developed. Using a depth camera and a custom-built system in MAX/MSP, the vertical deviation of a glass bubble was tracked and mapped onto sound, enabling glassblowers to hear the stability of their material while working.

The experimental process was conducted in a semi-naturalistic workshop environment with 15 participants of varying experience levels in glassblowing. Participants completed three stages: a control task, an experimental task with sonification, and an exploratory phase. Quantitative measures of movement deviation were combined with qualitative analyses of movement trajectories and participant feedback. The results suggest a differentiated effect based on expertise. While no overall performance improvement was observed across all participants, beginner glassblowers showed indications of improved stability when using auditory feedback, whereas experienced practitioners were largely unaffected. These findings suggest that the tool enhances only the performance of beginner glassblowers. In the exploratory stage, experienced glassblowers tended to work off-axis, suggesting either a wider error range or an emphasis on the sound aesthetics.

Beyond its empirical findings, this work presents processes within complex craft environments as viable objects of quantitative studies. The perspective on glassblowing as a site for human-material and human-human co-movement is a promising ground for further research. Through this perspective embodied knowledge can be addressed as a research domain, a methodological tool, and an artistic tool for expression.

This text constitutes the written component of the master's project. The project is extended in the graduate exhibition, where video recordings, sound clips generated during the experiments, processed movement trajectory images, and glass works are presented. Together, these elements allow audiences to personally encounter the relationships between movement, sound, and material.

## Biography

Rimon Alyagon Darr is a glass artist and cognitive scientist. Her works revolve around craft processes and engage the perceptive systems of the viewers in multiple manners. She holds a B.F.A in Glass Design and a B.Sc in Cognitive Neuroscience. Her academic activity includes a research assistant position in the psycholinguistics lab of Prof. Inbal Arnon, conference lectures in the TTT 2025 and BICCS 2025, an internship in the neuroaesthetics lab of Prof. Matthew Pelowski, a position in the research team of creative conversations with materials led by Prof. Michael Kimmel and participation in a course on embodied practices for doctoral candidates in the University of South-Eastern Norway, led by Prof. Camilla Groth. In the winter semester of 2026 she participated in an exchange program at Tama art university in Japan, where she conducted an experiment in the hot glass workshop of the university for her master's project. She is a member of Design in Gesellschaft, the Hof der Kulturen Alumni group, the Glass Art Society and the Homo Faber community.

# Meta Introduction

## What is my Approach to Interdisciplinary Research?

*During my master's studies, I was developing my own approach to interdisciplinary research and to being an artist-scientist. I was lucky to be surrounded by fellow students and professors who were either dealing with similar questions or working within their own frameworks and approaches to art and science.*

This thesis serves as a possible answer to the big question that accompanied my studies: What existing frameworks are there for interdisciplinary art-science practices, and where could I situate my own practice between those?

While my research acts as a feasibility study showcasing what I learned and integrated into my practice, this thesis envelops the study and includes a discussion of the theoretical frameworks which shaped my practice, as well as this study. This discussion begins with a definition of method for my artistic research and of the domains and recipients such research engages with.

## Art Research - What Does It Mean? Analyzing Through a Division into Three Subcategories

*During my bachelor's studies, I was studying both cognitive science and glass design. In an attempt to merge the disciplines, I was measuring*

*personal rhythms of beginner glassblowers and whether those change while working in dyads.<sup>1</sup> Treating my craft as a research domain felt like a rather superficial way of merging disciplines: one observes while the other is being observed. I knew from experience that one's rhythmicity was essential to their glassblowing. I did not know, however, how to explore this topic using methods, both artistic and scientific, in a manner which would remain rooted in art and science.*

In 1994 Christopher Frayling published an essay in the RCA publication addressing the vague term artistic research and its current meanings.<sup>2</sup> Frayling suggested a categorization system with which to approach artistic research. His formulation divided what he viewed as valid artistic research into three categories: (1) research into arts, (2) research through arts and (3) research for arts.

Research into art is what we mean, colloquially, when we say art research. Art history research, aesthetic research and similar works. The art or artist forms a research domain and the research is

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<sup>1</sup> Sai Sun et al., "Natural Finger-Tapping Tempo Reflects Intrinsic Neuropsychological Characteristics," Research Square, posted July 2, 2024, <https://doi.org/10.21203/rs.3.rs-4580693/v1>.

<sup>2</sup> Christopher Frayling, "Research in Art and Design," Royal College of Art Research Papers 1, no. 1 (1993-94).

done through a traditional academic discipline.

Research through art is research done within an artistic making process. For example, material research towards a piece or technique development.

In this case the artistic practice is the methodology, but the knowledge gathered is not the art piece itself, but rather the processes applied in the artistic making.

Research for art is the act of collecting knowledge or references to be integrated into a creative result. It is, then, not meant to be communicated, but embedded within a piece. The knowledge created is the art piece itself.

We can rephrase these three categories – research with art as the research domain, research with art as a tool, and research with art as a result.

Since Frayling's categorisation, many scholars, artists and designers have used and challenged his definition of artistic research. Prominent examples include Tess Colwell's study of her architecture students' practices while adhering to Frayling's framework, and Michael A.R. Biggs' artefact based approach as an alternative to

Frayling's formulation of research for art.<sup>3</sup>

Encountering Frayling's framework led me to expand my research and better understand my practice by following questions pertaining to domain, craft, and forms of knowledge production. I decided to challenge myself and involve aspects of all three categories in my artistic-scientific practice, planning out research endeavors that result in sculptures, material processing techniques, work tools, as well as reflections about my practices.

These questions led me away from the aforementioned manner of using scientific methods to study artistic practices in their function as mere domains. By considering artistic practices or craftsmanship as potentialities of embodied knowledge, a hybrid form of research presents itself. This hybrid treats the embodied experiences of a craftsperson as a vital, originary type of knowledge which can form both a basis for

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<sup>3</sup> Tess Colwell, "Research through, into, and for Design: Using Frayling's Framework to Explore Architecture Students' Design Research Methodologies," *Art Libraries Journal* 50, no. 2-3 (2025): 81-88. ; Michael A. R. Biggs, "The Rhetoric of Research," in *Common Ground: Proceedings of the Design Research Society International Conference at Brunel University*, ed. David Durling and Judith Shackleton (Stoke-on-Trent, UK: Staffordshire University Press, 2002), 111-118.

scientific inquiry and at the same time generate artefacts.

The following research has been a feasibility study of this hybrid practice. Glassblowing, as an artistic practice, maintains its multiple roles as: (1) research domain, (2) a research tool and (3) a beneficiary. I will return to these roles, observing how they manifested themselves in my research, in the discussion.

### Who Is This Research For?

*During my bachelor's studies I was working as a research assistant in a psycholinguistics lab studying language learning in adults. I was running the experimental data collection, which essentially meant explaining the experiment course and running it through with multiple participants. Many participants asked me what the research was for and if they would get their personal results, as if it was some form of test. I thought the wish to get the knowledge these participants took part in producing was a very intuitive wish. It made me wonder how scientific conduct can take more care through experimentation involving humans. The 'living lab' concept (Initiated in Boston but spread worldwide), where children and adults were invited to participate in research and ask the researchers questions about the latter's scientific domain, seemed like a step towards more communicative conduct, but did not completely settle my*

*thoughts on the topic.<sup>4</sup> I wondered how I could make the research experience into a tool that the participants could use as well. Running experiments on people while giving them minimal information about the objectives felt unfair. I wanted my research to feel less like exploitation but rather as a way to honour the research group, let it be visible, make the experiment enjoyable, let the participants play with the research tool and interpret it artistically. Furthermore, I wanted to bring the results back to the research group, with hope it can be of benefit or support to their community.*

Among the potential models for my planned research, I looked into participatory research approaches.<sup>5</sup> These usually involve an underrepresented community, approach a problem in a solution-oriented manner and address questions from the community, providing them with answers

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<sup>4</sup> Kathleen H. Corriveau, Becki Rebecca Kipling, Samuel Ronfard, Marta C. Biarnes, Brittany M. Jeye, and Paul L. Harris, "The Living Laboratory® Model," in *Cognitive Development in Museum Settings: Relating Research and Practice*, ed. David Sobel and Jennifer Jipson (New York: Psychology Press, 2015), 65–78.

<sup>5</sup> Flora Cornish, Nancy Breton, Ulises Moreno-Tabarez, Jenna Delgado, Mohi Rua, Ama de-Graft Aikins, and Darrin Hodgetts, "Participatory Action Research," *Nature Reviews Methods Primers* 3, no. 1 (2023): 34.; Rita Dhungel et al., "Hearing Our Voices: Pathways from Oppression to Liberation through Community-Based Participatory Research," *Space and Culture*, India 6, no. 5 (2019): 39–52.

gained through scientific research. Importantly, while I do want to give my community new possible lenses to look at their practice (artistic and scientific), I am not aiming for problem-solving.

The visibility of a community as one of the objectives of participatory research inspired me. I wanted my research to support the visibility of the glassblowing community as one that sustains endangered heritage practices. As many crafts are declared endangered, efforts to document and support them are becoming increasingly important. Recent initiatives such as The Making and Knowing Project and CRAEFT focus on documenting craft knowledge, while Crafting Futures explores connections between craft, science, and technology.<sup>6</sup> My work positions itself within this broader landscape, as a practice-based yet interdisciplinary contribution that

emerges from within the craft community itself.

The liminality of my role as a glassblower and a cognitive scientist allows me to approach glassblowing not only as an object of study but as a lived experience. In this way the research is done for both communities involved: the craft community and the scientific community, seeking to contribute meaningfully to each. This dual approach suggests methods of inquiry that rely on immersion in two realms. In autoethnography for example, personal experience becomes a source of knowledge. In practice-led research, practice and research evolve together. The hot glass workshop has already been the locus of practice-led research methods as well as autoethnographic inquiry.

A significant example is Erin O'Connor's autoethnography of her glassblowing learning years.<sup>7</sup> Her work provides an extensive documentation of her developing practice, and explores topics like human-material relations, social structures, and embodied experiences of skill learning in the hotshop.

Hulkkonen's et al. 2023 study focused on movement in the

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<sup>6</sup> Sara Wellman, review of *The Making and Knowing Project*, by Pamela H. Smith, *Renaissance and Reformation / Renaissance et Réforme* 46, nos. 3–4 (2023): 519–21 ; David Arnaud, Juan Carlos Bañón, Ioanna Demeridou, Arnaud Dubois, Danae Kaplanidi, Zoé l'Évêque, Sotiris Manitsaris, et al., CRAEFT, project website, accessed March 20, 2026, <https://www.craeft.eu> ; Will Hunt, Linda Ball, and Emma Pollard, *Crafting Futures: A Study of the Early Careers of Crafts Graduates from UK Higher Education Institutions* (London: Institute for Employment Studies, University of the Arts London, and Crafts Council, 2010).

<sup>7</sup> Erin O'Connor, "Embodied Knowledge: The Experience of Meaning and the Struggle toward Proficiency in Glassblowing," *Ethnography* 6, no. 2 (2005): 183–204.

hotshop, categorizing it by type and reasons.<sup>8</sup> While the mapping was detailed, the reasoning behind many movements remained unclear.

O'Connor's autoethnography and Hulkkonen's et. al's study intuit the potential of embodied experience as a base for neurocognitive inquiry, and the potential of neurocognitive knowledge to the practitioner's self-reflection.

Another important beneficiary of this research is the cognitive science community. My research acts as an effective feasibility study for a mixed-method approach in semi-naturalistic environments. A recent example in the specific field of synchronized movement is the movement tracking touch screen developed in the lab of Prof. Ayelet Landau and used to research the effect of individual neural tempo on synchronization performance between two people. This screen allows to accurately record synchronized movement.<sup>9</sup>

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<sup>8</sup> Kati Sara Sanelma Hulkkonen, Miia Lötjönen, and Maarit Mäkelä, "Sensing the Rhythm: Analysing Human and Non-Human Movement in a Glassblowing Process," *FormAkademisk* 16, no. 4 (2023): 1–10.

<sup>9</sup> Leah Snapiri, Yoav Shapira, Noa Dagan, and Ayelet N. Landau, "Similarity in Spontaneous Tempo Impacts Flow Experience and Coordination Dynamics during Joint Performance," *bioRxiv*, posted September 17, 2025, <https://doi.org/10.1101/2025.09.16.676074>.

Building such technological tools was prohibitively difficult to engineer in the past. Hence, a vast majority of past experiments is either observative and purely qualitative or takes place under strict lab conditions. The difficulty had to do with the array of challenges posed by the so-called noisy workshop environment compared to a lab environment.

Intervention based research was conducted by practitioner-researchers in workshop environments, but with an emphasis on qualitative or self-reported quantitative analysis. An example for such research is Camilla Groth's book exploring knowledge in making through multiple methods, including practitioner-researcher self run experiments in a pottery studio. The ongoing project Creative "Conversations" with Materials is another example, examining creativity in craft making through interviewing and observing the creative craft process, based on an understanding of the cognitive processes in craft making as embodied and environment dependent.<sup>10</sup>

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<sup>10</sup> Camilla Groth, *Making Sense through Hands: Design and Craft Practice Analysed as Embodied Cognition*, Aalto University publication series, Doctoral Dissertations 1/2017 (Helsinki: Aalto University, 2017). ; University of Vienna, "Creative Conversations with Materials," project page, accessed April 12, 2026, <https://ucrisportal.univie.ac.at/de/projects/creative->

The following research accepts the current viability of attempting quantitative research in a more naturalistic environment with a set task. While my research is a preliminary attempt, stepping out of the lab and into the craftsperson's workshop has, I believe, proven itself supportive of meaningful cognitive research that permits quantitative research into complex real life behaviours by limiting the task, the domain and the tool set.

The next sections are dedicated to some conceptual background - a practical explanation of the hot glass workshop (a.k.a the hotshop) and the active agents, both human and non human, within it. They will also refer to the relevant literature concerning itself with sensory-motor rhythm and synchronization mechanisms. These sections lay out a cognitive foundation as well as a craft-specific one. I then move on to the actual experiment, plan and execution.

# Domain Specific Background

## Describing the Hot Glass Workshop

A descriptive fragment of Hulkkonen's recent article on aesthetic experience in hot glass work:

*As my studio assistant opens the glass furnace door slightly, I adjust my vision to the bright orange light beaming inside the furnace... to prevent burning myself I take the third gather of molten glass from the furnace relatively fast.... When pulling out the third gather from the furnace and walking back to my work bench I balance my movements to prevent the molten glass run on the floor. I am aware of my offbeat groovy rhythm of movement that adjusts how and in which position I turn the blowpipe to keep the glass gather centered... I have visual awareness of my studio assistant with whom we are soon to take turns caring for the glass that is to become an execution of the scale drawing next to us. Caring for the glass involves an active awareness of the material. We tune our human senses to respect and meet the material movement of the glass."*

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<sup>11</sup> Kati Sara Sanelma Hulkkonen, "Sustaining the Poise: An Autoethnographic Inquiry into the Aesthetic Experiencing in Glassblowing," in Biennial International Conference for the Craft Sciences (2025).

In a classical hierarchical model, glassblowing is a group effort with set roles for the group members. The Maestro, main gaffer, will have one, or few, assistants. The glass piece created is the gaffer's creative property, therefore the gaffer directs the work and gives orders to the assistants.

The result is a multiple human agent network with an internal leading/led dynamic, the gaffer leading, and the assistants led.

In addition to these significant agents within the workshop, the glass is a main non-human agent. It is more dynamic than we imagine and prone to different factors, the main of which is temperature. As the glass temperature changes through the process, cooling down and being reheated, its viscosity increases and decreases and it moves faster or slower. In addition, since glass is not an efficient heat conductor, temperature variances within the glass bubble are bound to happen throughout the shaping process, which not only endanger the piece, but make it move unevenly. Hence, glass is a material with a rather wide range of behaviors.

As glass has multiple parameters determining its changing behaviour throughout the process, I will simply address it as an active agent, and its movement with the influence of the glassblower as a form of co-movement. I focus on this co-movement within the scope of my thesis, while acknowledging that the hot glass workshop involves both human-material and human-human interaction, each offering potential for further research.

In order to make the dynamic between a glassblower and glass somewhat clear before diving into the intervention process within the hotshop, I'll describe a segment of glasswork:

The glassblower takes the blowpipe, tilts it into the crucible of molten glass, and twists the blowpipe several times while adjusting the pipe back to horizontal position. The glass, in a viscosity similar to honey, drips until the mass that is on the pipe stabilizes, kept spherical due to surface tension. The pipe is then taken to the work bench, where it is placed horizontally on rails and turned constantly, to ensure that the glass at its end doesn't drip or

simply slope off-axis (see Figure 1). Since the viscosity of the glass changes, the pace of movement of the glass changes gradually, and the glassblower has to adjust their movement to the pace of glass to keep it on axis. The more a glass bubble is off axis the harder it is to control it, and, if desired, to bring it back to center.

While centering the glass, the glassblowers adjust their movement to that of the glass, creating a rhythmical pattern that changes with the glass's viscosity. But how does the glassblower perceive this pattern and react to it? Through which senses is the movement detected, what kind of information is processed and what mechanism allows a motor response of synchronized movement? And why does centering take years to master?

To answer these questions about synchronized, or rhythmical, movement to sensory information, I set out to explore relevant cognitive literature as a foundation for my research.



*Figure 1. Working with the workbench, rolling the pipe on the bench rail.*

## Sensorimotor Synchronization

Sensorimotor synchronization is, in simple words, adjusting our movements to an external rhythm intercepted through our senses and processed in our nervous system. Examples could be tapping to the music, moving synchronously to a movie clip etc.

The way we perceive information can heavily affect our ability to react. We may get quick and rough information from one sense and slow yet detailed information from the other. The ‘ideal’ sense for a task depends on the stimuli type and reaction type. In the case of synchronization to changing rhythm, the important factors are constant adaptation and low reaction times. Accordingly, the pace of sampling of the stimuli by the sensory system and the connection to the motor system play a vital role in online synchronization.

We humans have a rather rare ability to synchronize our movements to an external beat.<sup>12</sup>

<sup>12</sup> Léa AS Chauvigné, Kevin M. Gitau, and Steven Brown, “The Neural Basis of Audiomotor Entrainment: An ALE Meta-Analysis,” *Frontiers in Human Neuroscience* 8 (2014): 776; Aniruddh D. Patel, John R. Iversen, Micah R. Bregman, and Irena Schulz,

This ability is highly linked to speech, conversation and dance, and is correlated, though not exclusively, with synchronization between auditory and motor regions.<sup>13</sup> Multiple experiments conclude that it is easier for humans to synchronize to an external auditory beat than to a visual beat.<sup>14</sup> Additionally, the ideal sense for movement synchronization can vary according to the stimulus type (for example continuous vs. discrete), but in research including audio and visual output the multimodal audio-visual input yields the highest motor synchronization ability.<sup>15</sup>

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“Experimental Evidence for Synchronization to a Musical Beat in a Nonhuman Animal,” *Current Biology* 19, no. 10 (2009): 827–830.

<sup>13</sup> Neural Entrainment Determines the Words We Hear,” *Current Biology* 28, no. 18 (2018): 2867–2875; Nai Ding and Jonathan Z. Simon, “Cortical Entrainment to Continuous Speech: Functional Roles and Interpretations,” *Frontiers in Human Neuroscience* 8 (2014): 311.

<sup>14</sup> David Burr, Martin S. Banks, and Maria Concetta Morrone, “Auditory Dominance over Vision in the Perception of Interval Duration,” *Experimental Brain Research* 198, no. 1 (2009): 49–57; Bruno H. Repp and Amandine Penel, “Auditory Dominance in Temporal Processing: New Evidence from Synchronization with Simultaneous Visual and Auditory Sequences,” *Journal of Experimental Psychology: Human Perception and Performance* 28, no. 5 (2002): 1085–99.

<sup>15</sup> Manuel Varlet et al., “Continuity of Visual and Auditory Rhythms Influences

A plausible neural explanation on the phenomena lies in involuntary entrainment of the motor cortex by the auditory cortex, in other words, the neural synchronization process behind adjusting movement to sound happens (almost) effortlessly.<sup>16</sup> Another plausible explanation lies in the timekeeping mechanisms involved, claiming auditory information evokes more timekeeping mechanisms in the brain.

While aforementioned research was done with non-trained participants, other research was done on the effect of expertise, engaging trained experts as a research group. Hove et al. conducted a study checking the effect of visual and auditory rhythmic stimuli on the movement synchronization abilities of participants with visual (ball players and computer gamers) or auditory (musicians) expertise.<sup>17</sup> In

the research, participants (1) saw a bouncing ball, (2) heard a continuous metronome, (3) got visual and auditory cues with identical rhythm, or (4) got visual and auditory cues with different rhythms. In the auditory condition (2) both groups had better performance with less variable reactions than in the visual condition (1). In the distractor condition (4), visual experts were more distracted by the visual input, and auditory experts were more distracted by auditory input. Both groups were distracted by contradicting information, but the expertise changed the weight each sense was given in information processing for movement.

Centering the glass bubble while working with it is a rather difficult skill to master and one where sensorimotor synchronization takes a big part. The glassblower receives continuous visual rhythmical information from the glass's movement that changes periodically. The glassblower's rhythm of movement as well as correcting movements need to be adjusted to the changing pace of movement of the glass. As

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Sensorimotor Coordination," PLoS ONE 7, no. 9 (2012): e44082, <https://doi.org/10.1371/journal.pone.0044082>.

<sup>16</sup> Marija Pranjić, Thenille Braun Janzen, Nikolina Vukšić, and Michael Thaut, "From Sound to Movement: Mapping the Neural Mechanisms of Auditory-Motor Entrainment and Synchronization," *Brain Sciences* 14, no. 11 (2024): 1063.

<sup>17</sup> Michael J. Hove, John R. Iversen, Allen Zhang, and Bruno H. Repp, "Synchronization with Competing Visual and Auditory

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Rhythms: Bouncing Ball Meets Metronome," *Psychological Research* 77, no. 4 (2013): 388–398.

glassblowers, we have to heavily rely on our vision. Sound or tactile information, critical for metal turning or pottery, are of lesser use in glassblowing, since the glass bubble does not make a sound and is too hot to touch. But adapting rhythmical movement to visual information is rather difficult to do, while adapting movement to an auditory rhythm is significantly easier.

whether the effects described in this chapter replicated in the hotshop environment.

The research and studies outlined above, alongside my own experiences in the craft led me to wonder whether there is a way of creating sensory stimuli that are easier for glassblowers to follow with movement. In particular, I deliberated on a tool that would translate the movement of glass into sound. I was also wondering whether the level of expertise of the glassblower would have an effect on the significance of such a tool, taking into account that experienced glassblowers are trained to follow the visual cues that the glass offers. The only research I was familiar with on the effect of expertise on modal-dependent sensorimotor synchronization was done in lab conditions, and I was curious to put this tool to practical use and see





Figure 2. The experimental setup - bench, Kinect camera, computer and speaker.



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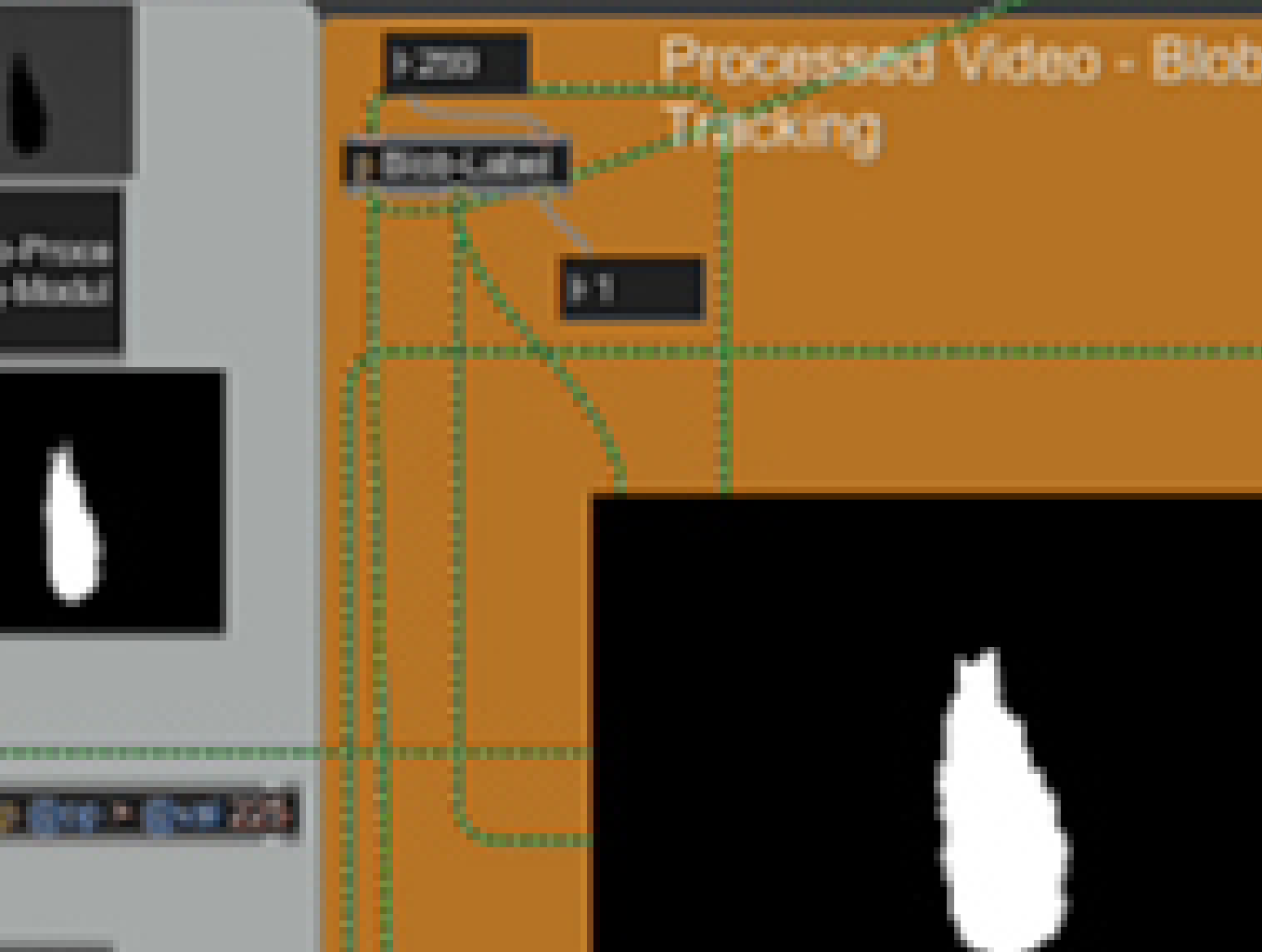


Figure 3. A screenshot from the running code in MAX/MSP during an experimental session.



# The Experiment

## Research Question

I decided to add auditory information about the movement of the glass bubble and ask the two following question:

*Can sonification of glass movement help glassblowers maintain a glass bubble on axis, and how does this differ between beginners and experts?*

*How does sonification alter human-material interaction in the hotshop?*

### Building the Research Tool

In order to sonify the glass' movement, I programmed a tool that captures the glass bubble on camera, follows its center point and generates a sound that changes in real time according to the height of the glass bubble.

The tool was built in MAX/MSP visual programming software. It was getting input from a Kinect camera, placed in line with the work bench (See Figure 2 and Figure 3 ).

The image is processed by a depth function, eliminating the background and keeping only the nearest object, that is the glass bubble. The captured 'blob' image is processed, its center calculated, and its y axis values are passed to a sound generator. As the bubble is rolled on the bench rail (see figures 4, 5 and 6), the bubble moves in a straight line if centered, or bobs up and down if it is off center. As a direct result, the sound stays stable if the bubble is centered, or the pitch goes up and down if the bubble is off axis. Small shifts in rhythm can be heard.

The sonification parameters were set by scaling the y axis range of values of the glass bubble to the range of 100-300 Hz and onto a sine wave generator. The result was a computer generated sound that has a significant range within it yet was not annoying to work with as a background noise. In test runs, higher frequencies were experimented with as well, but the pilot participants commented that the sound was unpleasant to work with over time.



*Figure 4. On/Off axis bubble image from the experimental video (top and bottom accordingly).*

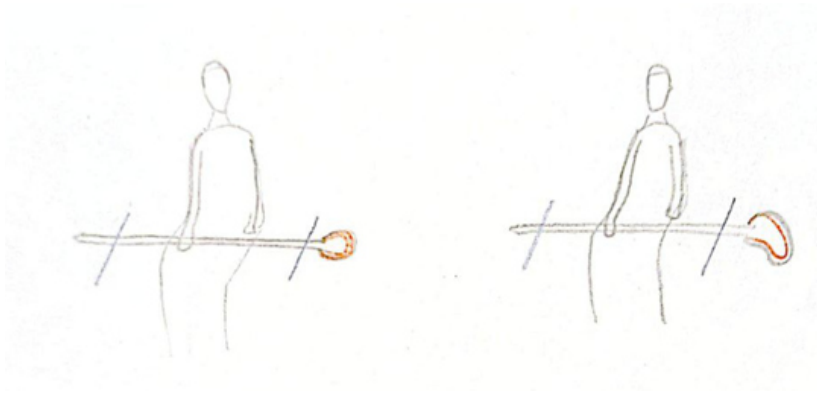


Figure 5. On/Off axis bubble illustration.

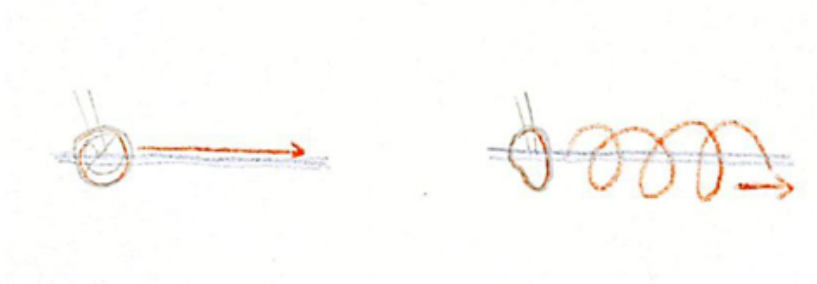


Figure 6. On/Off axis movement illustration.

## Experimental Design and Process

### *Participants*

All 15 participants were students of the glass course. The participants were categorized into experience groups: Beginners (1-2 years of experience, n=8) or Experienced (3+ years of experience, n=7). Participants were declared experienced from the third year of their studies onward. In the first couple of years of glass studies at Tamabi, the students are only learning foundations and are getting minimal practice times. From the third year on, they are expected to practice individually and develop their own artistic method, hence they are declared experienced. Participants joined voluntarily and received no monetary compensation. All students of the department were invited to participate through social media and could sign up through a registration form. My aim was to work with as many participants as possible and all the students who signed up joined the research.

### *Infrastructure*

The research was done in the months December 2025 and January 2026, at the Tamabi University's craft department. Since the workshop is a naturalistic environment, the experimental process is slightly less controllable. I eliminated the variance I could by setting the experiment in the same workshop bench, with the same work tools and using the same furnace. All participants were actively training within this workshop and therefore were familiar with it.

### *Design*

Participants were asked to answer preliminary questionnaires about their glassblowing experience and about their centering abilities, as well as providing consent.

The experiment had three consecutive stages. All participants did all three stages in the same order:

1. A control stage, where participants were asked to make a double gather of glass, blow a little bubble and roll it in a centered manner on the bench rails, without sonification
2. An experimental stage where participants were given the same task but with the sound tool activated.
3. An exploratory stage in which participants were invited to play with sound and shape.

Participants were explained how the sound is related to the movement of glass and were told they could use the support of the sound information if they wished to.

I chose to keep the aforementioned order despite a potential order effect problem for two reasons. First, centering is a highly practiced and routine skill in glassblowing, making substantial short-term improvement within a single session unlikely. Second, the gradual introduction of the sonification tool supported its integration into practice, thereby preserving ecological validity.

The process took about 30 minutes overall, but varied up to ten minutes between participants. Most of the variation was in the exploratory stage, as participants decided when to finish at their judgment, when they felt their creation in this stage was done.

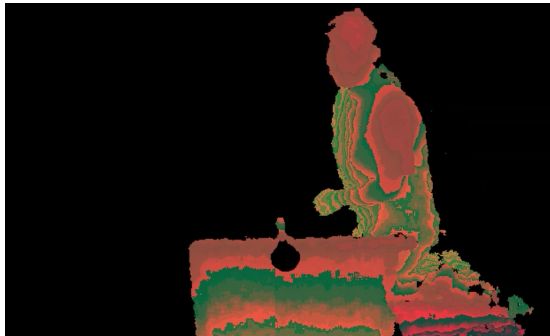
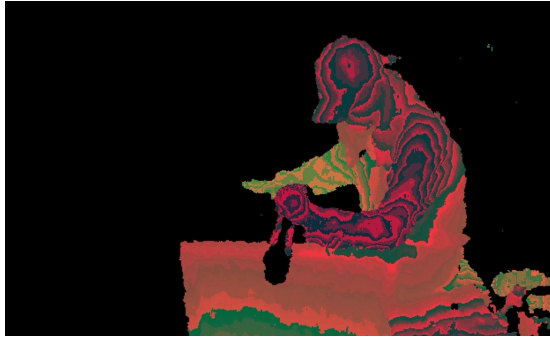
After the experiment participants were invited on a voluntary basis to fill in a feedback form including qualitative open questions.

### *Data*

The data collected was video information (Depth Camera, Video Camera, Blob Detection Video, see Figures 7 and 8) sound information (The sound that the glassblower heard during the work session) and the coordinates of the glass bubble throughout the whole session (see Figure 9).



Figure 7. Snippets from the video camera during the experimental process. The glassblower is rolling the pipe with the glass at its tip on the workbench rails.



*Figure 8.* Snippets from the depth camera during the experimental process. The glassblower is rolling the pipe with the glass at its tip, the glass appearing as a dark blob, on the workbench rails.



*Figure 9. Trajectories of movement, off-centered (top) and centered (bottom), of the glass bubble. These are post-produced images using the coordinates of the glass bubble over time.*

## Results

Two participants were excluded from the quantitative analysis due to missing recordings. 60% of the participants stated that centering is a difficult task for them.

The results were analysed in five different ways:

1. Across stages analysis: the performance of the entire participant pool with and without the sonification tool.
2. Across stages and within participant analysis: The personal difference in performance for each participant with and without the sonification tool.
3. Across stage and across group analysis: the difference in maximal deviation in beginners in comparison to experienced glassblowers with and without the sonification tool.
4. Qualitative analysis across stages: qualitative analysis of movement trajectories across groups and stage.
5. Qualitative Analysis of the exploratory stage: a qualitative analysis through two case studies of off-axis behavior.

All quantitative analysis was done without assuming group normality, due to the small research sample ( $n=13$ ).

### *Across Stages Analysis*

The entirety of the research group ( $n=13$ ) did not show a trend either in mean deviation of y axis values (Control=5.31, Experimental=5.16) or in Standard Deviation (Control=1.3, Experimental=1.6 ) between the first two experimental stages. Hence, no positive trend in performance was observed among glassblowers while using the sonification tool.

### *Across Stages and Within Participant Analysis - Stage A (Control Stage) to Stage B (Experimental Stage with Sound)*

The following graph shows the difference in mean deviation between the two experimental stages for each participant, with the y axis presenting years of experience (see Figure 10). In beginner glassblowers (1-2 years of experience,  $n=7$ ) we can see a positive mean difference, suggesting a possible positive effect of the sound tool. In the experienced glassblowers ( $n=6$ ) we see a slight negative trend, suggesting a possible negative effect of the sound tool. The observed positive trend suggests improved performance in beginners while using the sound tool.

To further test the correlation between the years of expertise and the difference in mean deviation I ran a Spearman correlation test and received the result of  $\rho = -0.656$   $p = 0.0147$ . Since the correlation coefficient is negative and  $p < 0.05$ , a significant negative effect is observed, meaning that the more years of expertise a glassblower has, the less effect the sonification had on their performance.

### *Across Stage and Across Group Analysis - Stage A (Control Stage) to Stage B (Experimental Stage with Sound)*

As seen in the following graph, the most salient trend was the difference in maximal deviation across groups and stages (see Figure 11). The parameter of maximal deviation shows the general stability of a participant by its most extreme sloping off axis, and can hint on how early the off-center sloping was perceived and handled. In the beginner group we can see a negative trend in the maximal deviation between stages A and B, suggesting less extreme deviations while using the sound tool. In the experienced group we see an incremental negative trend between the two stages. In simple words, this suggests the tool increases overall stability, with a bigger effect on beginners than on experienced glassblowers.

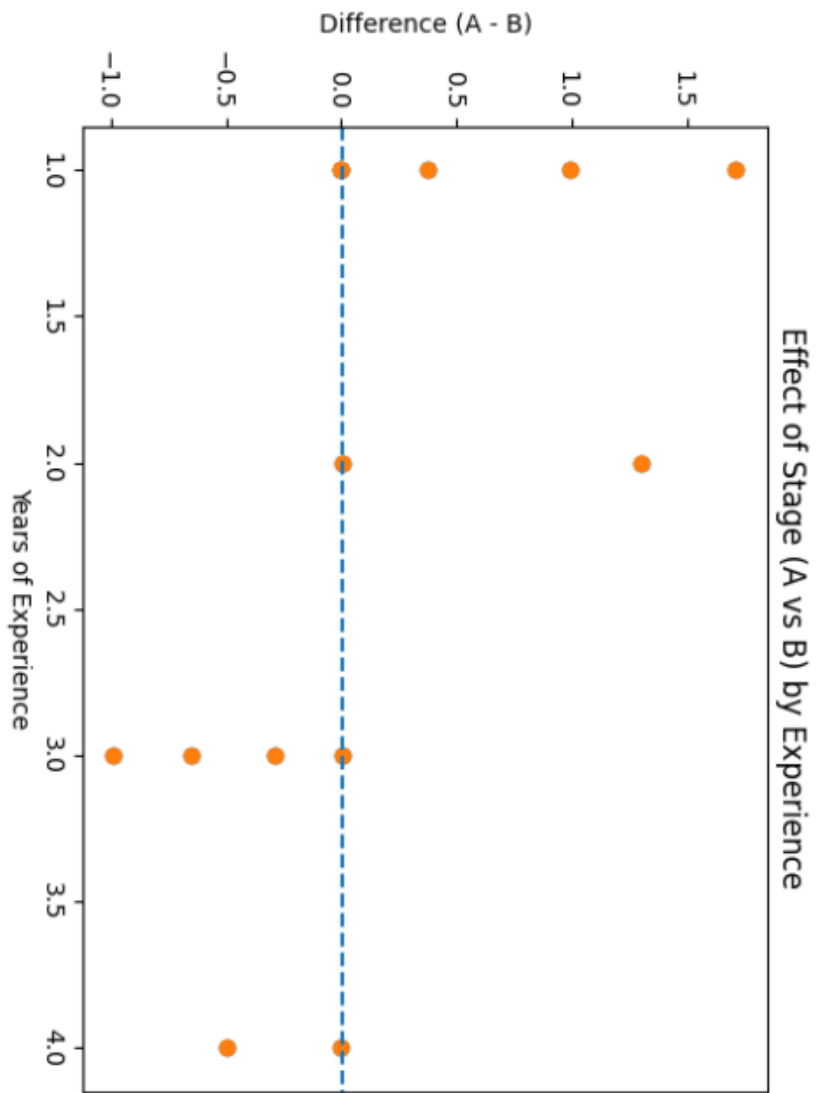


Figure 10. Effect of stage (difference in mean deviation) across years of experience of the participant.

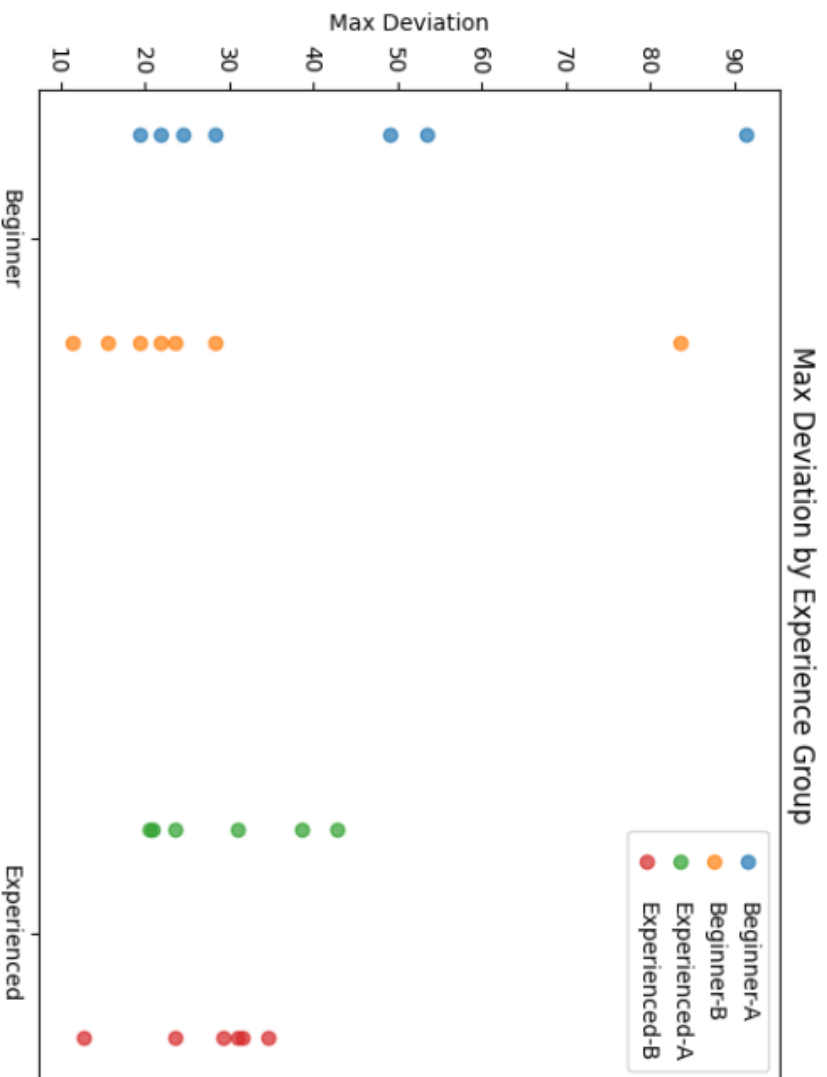


Figure 11. Maximal deviation in beginner and experienced glassblowers within the two experimental stages.

To check the statistical significance of the performance difference across groups and stages, I ran a Mann-Whitney U test across groups and stages that gave the p value of  $p = 0.0123$ . Hence the positive effect of the sonification is significant across groups and stages as well.

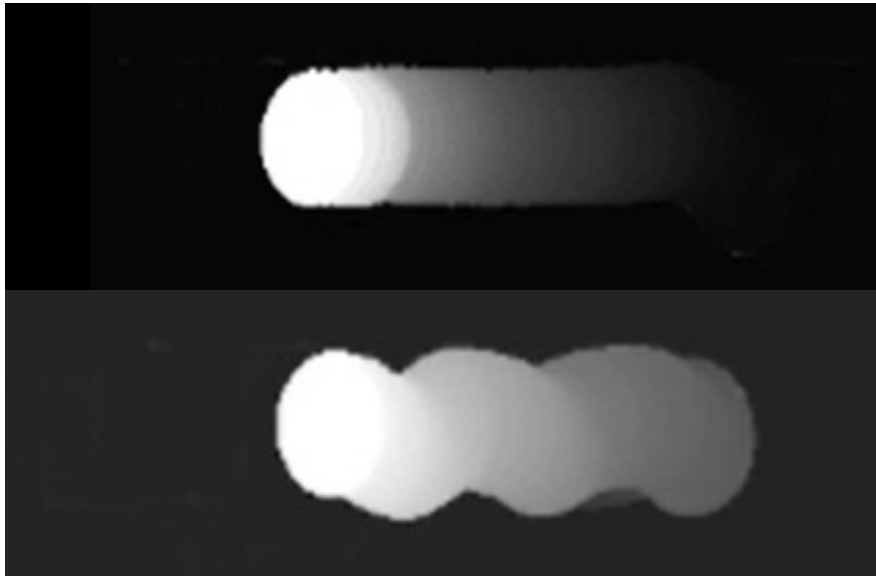
#### *Qualitative Analysis - Movement Trajectories Across Groups and Across Stages A (Control) and B (Experimental)*

The results were explored qualitatively by processing the x and y values of the glass bubble into movement trajectory images. A comparison was made between the trajectories of beginner and experienced glassblowers across both control (see Figure 12) and experimental (see Figure 13) stages. This qualitative material is further developed in the exhibition, where it offers the audience a way to engage with and 'feel' the data. In this section I present one example focusing on the movement trajectories of a beginner and an experienced glassblower across the two stages.

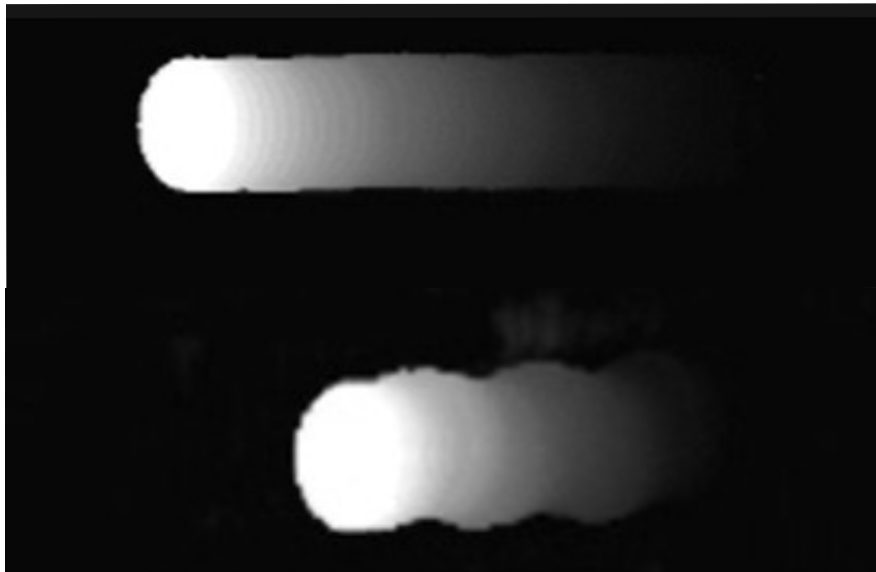
The pattern created by rolling the glass pipe on the bench rails appears more stable when executed by an experienced glassblower than by a beginner. The performance of the beginner glassblower seems to improve when the sound is present, whereas the performance of the experienced glassblower remains largely unchanged. This observation corresponds with both the experimental data and the feedback provided by the participants. Beginner glassblowers reported attending to the sound and finding it helpful, while experienced glassblowers described it as background noise and indicated that they did not actively pay attention to it.

### *Qualitative Analysis of the Exploratory Stage*

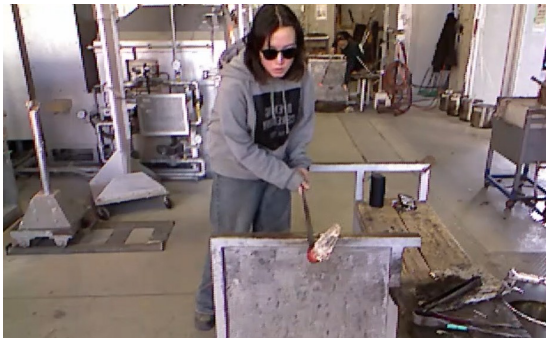
Stage 3 is a purely exploratory stage. The behavior of the participants is approached qualitatively, based on examples from the experimental video recordings. Within this exploratory phase, I observed two main approaches: Exploration with shape as a primary factor, and exploration with sound as a primary factor. Exploration through sound often led to strongly off-axis handling of the material. This tendency was observed only among experienced participants, who produced objects that were, either during the process or in their final form, distinctly off-axis (see Figure 14).



*Figure 12. Experienced (top) versus beginner (bottom) glassblowers glass's movement on the bench rail, control stage.*



*Figure 13. Experienced (top) versus beginner (bottom) glassblowers glass's movement on the bench rail, experimental stage.*



*Figure 14. Off-axis work in experienced glassblowers during the exploratory stage.*



*Figure 14.* Off-axis work in experienced glassblowers during the exploratory stage.

# Discussion – Within the Scope of the Study

## Across Stages Analysis

The research group's average performance did not change due to the sonification of the glass's movement when including both experienced and inexperienced glassblowers. This implies that the tool does not offer overall improvement in centering performance.

## Across Stages and Within Participant

Returning to the study by Hove et al., the observed positive trend present in beginner glassblowers and no trend in experienced glassblowers matches the results of the study, suggesting that the hierarchy between different cue modules in a multimodal environment changes through becoming an expert in a unimodal skill. <sup>18</sup>Seeing this trend out of the lab, in a semi-naturalistic environment, strengthens the assumption and suggests our sensorimotor synchronization abilities can change with gaining expertise in a skill or a craft. If so, mastering a craft means changing the way we perceive the world and react to it.

The qualitative results provide further support to the trend observed in the data, but have a further value, allowing us to sense the data. Qualitative insight can clarify what expertise in a skill consists of. Is centering as an expert related to continuous motion, fast corrections in discrete motions, or rather to keeping the slope of the bubble in a specific range? Isolating the motion from the human and non-human agents involved allows us to examine its qualities as a form of movement and comparing skilled and unskilled movement.

## Across Stage and Across Group

While the maximal deviation in the experienced glassblowers group was low and showed no effect in the experimental stage, the beginner group's maximal deviation reduced significantly with the sonification.

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<sup>18</sup> Hove et al., "Synchronization with Competing Visual and Auditory Rhythms," 392.

Since this is the most significant trend observed, a plausible explanation for an improvement in performance lies in less extreme off-center incidents rather than the ratio of on-center/off-center moments. These are achieved by noticing the slope earlier and handling it on time. It is possible that a trend was not observed in the experienced glassblowers group as their maximal deviation was rather small from the start, possibly because of mastering the skill of noticing and reacting to the slope of the bubble off-center, and possibly due to a better adjustment of movement to the constantly changing rhythm of glass movement. Thus, the tool may not be an entrainment or synchronization tool per se, but rather an attentional tool, directing the inexperienced glassblower to pay attention to the sloping off of the glass bubble.

### The Exploratory Stage

The exploratory sessions and their outcomes will be exhibited in the master's exhibition, allowing the viewers to reflect on the relationships between making processes, the sound generated by the movement of the glass, and the sculptural glass objects produced in the session.

During the exploratory stage, participants, especially experienced ones, tended to work exceptionally off-axis, which made the sound less stable. This could be supporting one of two hypotheses: one is that the sound became a more interesting domain to explore than shape, and therefore the aesthetic qualities of the sound were more interesting than the aesthetics of the shape. The second hypothesis is that the sound allows the glassblower a wider range of off-axis movement, as the signal can aid recentering.

### Further Research Ideas and Possible Uses of the Tool

While the tool is helpful in a multimodal supporting environment (vision and sound that provide supporting information to one another), further experimentation both artistic and scientific could be done with the tool, for example by running the same procedure blindfolded or creating a sculptural piece based on the sound rather than on

vision. More complex multimodal experimentation could be conducted, providing contradicting information through the sound and checking how much weight a beginner glassblower attributes to the sound in comparison to an experienced glassblower.

Further exploration of the relation between shape, creation sound, and making videos within those sessions could be further analysed in following research.

Observing the off and on axis forms that emerge through interaction with the sound tool suggests that it can support centering practice in beginners, while affording off-center expression in more experienced practitioners. Within the centering support for beginners, further research can determine whether the tool is beneficial for learning, hence improves general performance without the sonification tool over training time, or rather if it enhances performance only while using the tool, and does not facilitate learning.

In addition, questions about the sound and video clips and their artistic value are beneficial for further pursuing the sonification tool's artistic and performative value. It can also create a hybrid form of art, linking durational work to an artefact.

# Meta-Level Discussion

## Reflection on My Interdisciplinary Practice

In my search for a hybrid practice of art and science through my studies and specifically this project, I identified the embodied knowledge I carry as a craftsperson as a significant linking point between my practices. While collecting references, I encountered a few projects on the topic of rhythmicality, sound and process emphasis in glassblowing. They were all initiated from a practitioner's view, and the outcomes were either artistic, craft based or scientific.

One of the relevant works in the artistic realm is Alexander Rosenberg's *Composition for a Glass Tumbler*, a piece aiming at creating a musical composition out of the happenings in the workshop, using computer vision tools.

<sup>19</sup>Rosenberg filmed a session, divided the video frame into keys and translated the sound onto musical notes, displaying the composition with the object created in the session. Rosenberg's work and mine share a fascination with the rhythmical movement aspect of glass and a wish to keep the qualities of the glassblowing process in the finished piece.

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<sup>19</sup> Alexander Rosenberg, *Composition for a Glass Tumbler*, 2010–2014, hand-blown glass, print, and performance-based work, artist website, <https://alexanderrosenberg.net/Composition-for-a-Glass-Tumbler>.

Another work worth mentioning in the art-craftsmanship-design realm is Philipp Weber's *Strange Symphony*. Weber created a glassblowing pipe that has trumpet-like valves, allowing the glassblower to 'play' the pipe resulting in a different shaping of the glass piece and the air cavities within it. As written in *Dezeen Magazine*, "Weber also sensed a strong rhythm and musicality in the way Genard was working on the glass. The pipe as a tool for glass production, appeared to be like a musical instrument to him. He could not resist the idea to translate the mechanism of a trumpet into an application for blowing glass."<sup>20</sup>

In the scientific realm, the aforementioned works of Erin O'Connor and Sara Hulkkonen explore rhythmicality in the hotshop from situated perspectives, through autoethnographic and practice-based approaches.

The sensorimotor mechanisms involved in glassblowing occupy a central role in the development of craft skills and knowledge. In this context, embodied experience has the potential to inspire research and exploration within the domain of cognitive sciences. The

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<sup>20</sup> Philipp Weber, "Strange Symphony: Musical Glassblowing Pipe," *Dezeen*, June 12, 2013, <https://www.dezeen.com/2013/06/12/strange-symphony-musical-glassblowing-pipe-philipp-weber-dmy-berlin/>.

craftsperson's way of perceiving, processing, and acting in the world constitutes a form of knowledge that is largely accessible only to them, unless it is externalized. This knowledge is continuously shaped and transformed through the objects they create and their interactions with the environment.<sup>21</sup>

Looking at the embodied experience as the core of a craftsperson's experience allows us to create tools that alter the manner the information is received rather than altering the information or the reaction per se. This way, cognitive knowledge about the perceptive system and sensorimotor synchronization can be applied onto support tools for craftspeople, through manipulations or transduction of sensory information.

### Artistic Research

Frayling's framework provided a useful structure for reflecting on and developing this project, and I return to it in the discussion, examining the study through the three categories of research: into, through, and for the arts.<sup>22</sup>

The small-scale cognitive study conducted in the hot glass workshop can be understood as research into the arts, as it

<sup>21</sup> Groth, "Making Sense through Hands."

<sup>22</sup> Frayling, "Research in Art and Design."

investigates rhythmicity within glassblowing practice, treating the craft as a research domain.

The sonification tool developed in this study enables both the reflection on and documentation of centering, a skill that is essential to glassblowing and represents a form of embodied knowledge. At the same time, it opens up a new mode of creation, where the process itself along with the sound it generates becomes the artistic outcome. In this sense, both the tool and the knowledge it produces can be understood as research through the arts, particularly in the exploratory phase where making and experimentation are central.

The artistic, cognitive, and technical knowledge generated throughout the project can be seen as research for the arts, manifesting in the video, audio, and glass works presented in the graduation exhibition.

At the same time, these categories do not remain strictly separate. The experimental setup and its scientific method position the work as research into the arts, while the development of the sonification tool and its potential applications (as a training aid for beginners or an expressive medium for experienced practitioners) extend it into research through the arts. The preparatory research and tool-

building processes further contribute to research for the arts. In this way, the project demonstrates how knowledge can move across disciplinary boundaries, allowing these categories to overlap and inform one another.

### Who Was This Research For? Returning to the Question of the Research Recipients

In the introduction I stated that the question who the recipients of this research are, is a question that guides my way through the experimental query and design.

My wish to make this research for the glassblowing community was addressed in several actions. The experimental design attempted to make the participation an enjoyable, playful and insightful experience for a glassblower, allowing reflection on their own aesthetic experience in hot glass work. The experimental tool was planned in a manner that could be used in any glassblower's home studio, making it accessible. In order to do so I made sure to use software that has free access, a depth camera that is in domestic use (Kinect), and built an algorithm that is both stable and adjustable to different placements of equipment. I hope to be able to spread the tool between different workshops, hearing insight and seeing creative results produced

while using the tool. The aforementioned works of glassblowers like Alexander Rosenberg and Sara Hulkkonen manifest interest of the glassblowing community in rhythm and sound in the hot glass workshop. My thesis is a part of a community effort of creating a wider array of knowledge on the topic. I hope to pursue further research on movement in hot glass work, integrating human-human and human-glass rhythmic interactions.

As for the cognitive science community - this research serves as a successful proof of concept for conducting quantitative research in semi naturalistic environments. It serves as an invitation to use technological tools that have recently become available to the public. It also enables tracking and quantifying movement in complex environments that often hold access to specialized practitioners, and how learning shapes their perceptive system. This approach can support cognitive scientists exploring craft making, but can also expand to any practitioner-scientist project, allowing both groups to create and receive knowledge from and about the other.

Throughout my master's project, I had the chance to look at my creative practice as a research domain, use my cognitive

knowledge for my creative practice and community, and create a tool that can enable both creative outcomes and scientific research. I hope to further develop my joint practice out of true respect to the communities that taught me the skills I use in my everyday practice, hopefully bringing them insight that derives from my interdisciplinary stance.

Thank you for reading.



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# Appendix

## Statistical Analysis Programming Code

The full code written in Python is available through the following link or QR code:



[https://gist.github.com/RimonAD/  
6c3fofo0286886of10002f417ec9db5b](https://gist.github.com/RimonAD/6c3fofo0286886of10002f417ec9db5b)