LOUVAIN RESEARCH INSTITUTE IN MANAGEMENT AND ORGANIZATIONS

WORKING PAPER

2025/15

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LOUVAIN RESEARCH INSTITUTE IN MANAGEMENT AND ORGANIZATIONS

Louvain Research Institute in Management and Organizations
Working Paper Series
Editor: Prof. Karine Charry
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Summary

Cubic tangible interfaces are a promising yet underexplored modality in educational settings that could inform their development. This paper investigates gestural interaction with cubic objects, specifically AudioCubes, in learning contexts. Using the Goal-Questions-Metrics framework as a foundation, this study employs a systematic literature review, gesture elicitation studies, and usability evaluations to determine how cubic tangible interfaces can be adapted to meet the needs of diverse users in various educational contexts. It examines how cubic tangible interfaces can support learning activities by identifying preferred gestures and movement patterns across various tasks and user contexts. This highlights the need for a structured engineering methodology that supports the creation of reusable, generalizable cubic tangible interface designs, moving away from one-off designs that are often valid only for a particular case. The study classifies core gesture types using µGlyph notation to enable consistent representation across tasks. Usability assessments reveal common issues, user preferences, and ways to enhance user immersion. Furthermore, the research emphasizes adapting interfaces for diverse users, especially younger learners and individuals with different motor or cognitive abilities.

Keywords: Cubic tangible interaction. Gesture input. Learning activities. Tangible user interfaces.

JEL Classification:

We acknowledge support by the EU EIC Pathfinder-Awareness Inside challenge "Symbiotik" project (1 Oct. 2022-30 Sept. 2026) under Grant no. 101071147.

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Towards Gestural Interaction with Cubic Tangible Objects in Learning Activities

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Abstract. Cubic tangible interfaces are a promising yet underexplored modality in educational settings that could inform their development. This paper investigates gestural interaction with cubic objects, specifically AudioCubes, in learning contexts. Using the Goal-Questions-Metrics framework as a foundation, this study employs a systematic literature review, gesture elicitation studies, and usability evaluations to determine how cubic tangible interfaces can be adapted to meet the needs of diverse users in various educational contexts. It examines how cubic tangible interfaces can support learning activities by identifying preferred gestures and movement patterns across various tasks and user contexts. This highlights the need for a structured engineering methodology that supports the creation of reusable, generalizable cubic tangible interface designs, moving away from one-off designs that are often valid only for a particular case. The study classifies core gesture types using µGlyph notation to enable consistent representation across tasks. Usability assessments reveal common issues, user preferences, and ways to enhance user immersion. Furthermore, the research emphasizes adapting interfaces for diverse users, especially younger learners and individuals with different motor or cognitive abilities.

Keywords: Cubic tangible interaction · Gesture input · Learning activities · Tangible user interfaces.

1 Introduction

Tangible Interactions have been widely studied in general with all kinds of different objects equipped with different sensors in different application domains [4]. However, less is known today about the use of one particular object, namely a tangible cube, in learning activities [9]. To study this interaction with a tangible cube as part of learning activities, we need to define and follow a method for engineering the tangible interface with this object to move away from one-off approaches, often valid for a particular case, which are difficult to reuse or generalize to multiple experiments. As a specific form of tangible user interface (TUI), the cube facilitates interaction through physical gestures like moving, rotating, and positioning. It is regarded as one of the easiest graspable objects

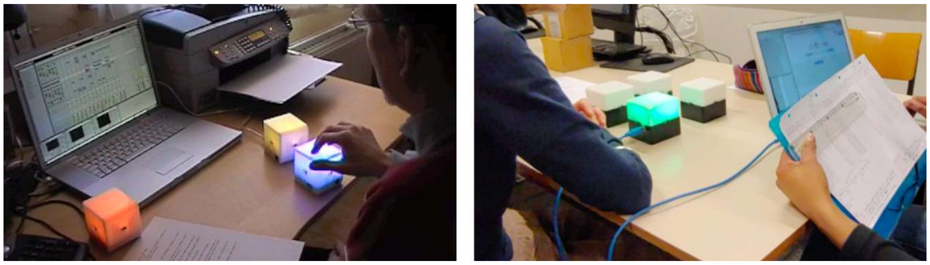


Fig. 1. Two cases of cubic tangible interaction: sound design (left) and learning (right).

for humans [5], offering intuitive interaction by aligning physical manipulation with cognitive processes [5]. This makes it both easy to adopt and cognitively acceptable [7]. The cube's main strengths are its support for distributed interaction, multiple physical configurations, two-handed use, immediate spatial and haptic feedback, and multi-user capabilities (see Fig. 1 for two examples). This versatility arises from its capability to serve as input devices, output displays, or both, depending on the applications [3,2,8].

These characteristics foster dynamic interaction environments that blend physical, digital, and cognitive aspects, thereby improving engagement and knowledge retention in educational contexts. This aligns with Montessori's (1912) emphasis on the use of manipulative tools for self-directed learning) [18]. Pioke et al. underscore the significance of learning media in overcoming challenges posed by abstract mathematical concepts, particularly cube and block nets, which are vital for developing spatial reasoning. Their research demonstrates that such tools substantially boost students' understanding and problem-solving capabilities in mathematics [19].

Jean Piaget's constructivist theory of cognitive development posits that learning is facilitated through students' direct interaction with tangible objects, rather than merely receiving information passively. Piaget's theory emphasizes that learning occurs through active engagement with physical objects, enabling students to construct their own understanding. For instance, students grasp concepts like addition by physically manipulating objects, which helps develop their logical and mathematical reasoning [27]. Likewise, Walsh and Magana demonstrate that using concrete objects enhances the understanding of physics concepts, such as friction [20] (see table 2). In light of these considerations, it is essential to investigate the following research question:

RQ = How can cubic tangible interaction be adapted to end-users in learning environments?

Using the Goal-Question-Metric (GQM) framework, we break this question into focused sub-questions, elaborated in the following subsection. To guide this exploration, we propose **hypotheses** that examine gesture-based interactions with CTI in learning contexts and their adaptability to diverse users:

H_1: The Characteristics of a cube: Size, shape, design, and material influence the range and nature of gestures performed by users during learning activities

H_2: The complexity of gestures such as rotating, moving, or task-specific actions varies depending on the learning activity and interaction context.

H_3: User characteristics, including age, physical abilities, cognitive capacities, and preferences, affect gesture patterns. Adaptive interfaces are necessary to accommodate diverse needs, particularly for younger users or those with limited motor skills.

H_4: Effective gestural interaction in learning requires a structured approach to gesture classification. This supports intuitive, adaptable interactions tailored to educational contexts, improving user experience and engagement.

1.1 Research Question

Following the Goal-Questions-Metrics (GQM) [1] framework, a hierarchical model that follows a top-down approach where a goal is first specified and associated with research questions collected and measured through metrics, this thesis makes the following contributions aligned with research program tasks:

Table 1: GQM Framework: Understanding and Adapting Cubic Tangible Interfaces

Goal	Understanding Cubic Tangible Interaction (CTI)	Study user interaction and gesture-based interactions with CTI in general, and with AudioCubes across different learning contexts	Adapt the Cubic Tangible Interface (CUI) to the end users' needs
Questions	– **RQ1**= What are the current use cases of CTI? – **RQ2**= How do they differ from other TUIs?	– **RQ3**= What gestures do users naturally perform with AudioCubes in learning tasks? – **RQ4**= How can these gestures be effectively described and classified?	– **RQ5**= What is user experience?

Tasks	Perform a Systematic Literature Review (SLR) on main digital libraries (e.g., ACM, IEEE, ScienceDirect) (**T1**)	– Perform additional Gesture Elicitation Studies (GESs) – Create replications of the initial GES in new configurations (RepliGES framework) – Consolidate results into a classification of CTI gestures – Develop MIDI interface and create usage datasets (**T2**+**T3**)	– Create a dictionary of cubic gestures – Define all configurations using the µDEX software – µGlyph notation (**T4**)
Metrics	– Number of papers by category – Classification of papers * Metrics reported in the PRISMA flow diagram	– Agreement rate – Thinking time – Goodness of fit – Perceived gesture complexity	– Task completion rate and time – Fatigue – Memorability – Actual gesture complexity

2 Related Work

Based on our preliminary research, cubic shapes have been widely used in the design of tangible interactive devices, offering significant potential in education [22]. However, their application remains underexplored, particularly regarding systematic gesture studies and user adaptation.Kranz et al. [2]developed a cube as a tangible user interface with six LCD displays and accelerometers for edutainment applications. The study emphasizes the interface's hardware setup, gesture-based input, and visual output capabilities discussing the cube's potential applications, particularly in educational settings, such as edutainment for children through picture recognition, vocabulary training, and matching 2D views. However, the study lacked extensive user testing across diverse contexts. Similarly, Zhou et al. [24] introduced a 3D story cube for interactive storytelling to enhance narrative-based learning, focusing on designing and implementing two tangible interactive entertainment interfaces using physical cubes: The Magic Story Cube and the Jumanji Singapore. These systems combine tangible user interfaces (TUIs) with augmented reality (AR) to create multi-sensory, engaging experiences.They have primarily focused on designing and developing CTI with priority to entertainment over education and do not systematically explore gesture studies. Schiettecatte & Vanderdonckt [6] explored AudioCubes, which combine spatial manipulation with auditory and visual feedback, enabling gestures like tilting or stacking to trigger specific outputs (e.g., sounds or lights). Their work highlighted the cubes' ability to sense proximity-forest-and-finger-proximity, but focused on the music domain

A systematic literature review by Villarreal-Narvaez et al. [28] analyzed 216 gesture elicitation studies (GES) involving 5,458 participants and 148,340 elicited gestures, providing insights into user-defined gestures for devices like smart rings and deformable displays. Notably, this comprehensive analysis does not reference cubic or cubic tangible interfaces, indicating an underexplored area for gesture elicitation with three-dimensional, cube-shaped TUIs, which could leverage unique spatial and tactile properties for educational applications. The review also reveals limitations in GES that are relevant to developing gesture vocabularies for CTIs. Many GES focus on eliciting a single gesture per referent, which may restrict the exploration of multimodal or multi-symbol interactions that could enhance the expressiveness of cubic interfaces. The reliance on manual agreement measures, such as the agreement score (34%) and agreement rate (51%), may overlook nuanced gesture variations due to subjective clustering. Furthermore, the absence of longitudinal studies to evaluate gesture retention over time and the emphasis on specific devices (e.g., smartphones, TVs) and gesture types (e.g., hand, mid-air) limit the generalizability of findings to novel TUIs like CTIs. These gaps highlight the need for targeted gesture elicitation studies to optimize the design of cubic interfaces for educational contexts.

Camarata et al. [26] used cubic blocks for spatial navigation in virtual museums, while in computer science education,Mateu and Alaman [23] employed tangible cubes to teach sorting algorithms, making abstract concepts more concrete and engaging. These studies reinforce the educational value of CTIs and their ability to assist pedagogical activities, but do not explicitly investigate how user gestures should be defined or adapted. Additionally, they do not provide comprehensive usability testing across diverse educational settings. Shuqi et al [31] investigate the use of tangible cubes in mixed reality (MR) environments for intuitive data interaction. Their work offers a systematic framework for understanding gesture interactions with CTI, directly addressing the need for targeted gesture elicitation studies in this area. It emphasizes the cubes' suitability for exploring multi-dimensional data due to their maneuverability and stable structure. While the primary focus was on data visualization, the methodologies and insights gained from this work can be applied to educational contexts, particularly in designing intuitive and adaptive gesture-based interactions for learning tools.

In contrast to cubic designs, non-cubic TUIs have demonstrated significant potential in educational contexts, offering insights that could inform CTI development. Ayala et al. [29] explored the FlyStick and PrimBox, two tangible interfaces for teaching geometry in secondary schools. The FlyStick allows control of virtual objects in six degrees of freedom, while the PrimBox enables modification of object attributes like position and size. Their pilot study showed improved knowledge retention through gesture-based interactions, suggesting that similar benefits could be achieved with cubic TUIs if gesture design is prioritized. underscoring the pedagogical potential of well-designed TUIs.

Table 2: Review of two recent studies with Cubes in Educational Settings

Study	Gesture Type	Learning Context &objects	Learning Gains
Pioke et al.,2021	– No mention found(concrete object manipulation)	– Cube and block nets in mathematics	– significant improvement – enhance understanding – made abstract mathematical concepts more accessible and engaging
Walsh and Magana, 2023	– Physical manipulation – Visuohaptic simulation *Not explicitly described or classified	– Friction concepts in physics/Cube	– Significant gains in understanding friction variables(force, speed, acceleration, distance)

3 Theoretical, Conceptual, and Empirical Contributions

To carry out this research project, we have chosen AudioCubes because they represent a distinctive form of cubic tangible user interface, integrating spatial and auditory interaction modalities [6], making them a compelling example of tangible interfaces for Human-Computer Interaction (HCI) in learning environments. Thus, beyond their usual features as a cube. They merge as a versatile and promising physical object due to their symmetrical shape and rotational axes. Unlike conventional cubes, AudioCubes are wireless, battery-powered devices embedded with a computer within a plastic enclosure. They feature built-in sound and general-purpose signal generation and processing capabilities, and each face is equipped with a full-color light source that provides continuous visual feedback. In addition, AudioCubes are engineered to sense the position and orientation of other cubes, as well as the proximity of hands, fingers, and other objects [11]. We can use Audiocube across different learning scenarios, which are inspired by and built on prior works [19,20] :

- **In a math learning scenario**, AudioCubes could teach arithmetic through gestures. For instance, placing one cube on the table might represent the number 1, and aligning a second cube next to it yields 2; each arrangement triggers corresponding spoken numbers or sounds. Rotating a cube by one step could add a value or cycle through arithmetic operations, linking physical rotation to numeric concepts.

– **In language or literacy activities**, AudioCubes can represent letters or words. Each face of a cube could correspond to a phoneme or letter. A student could tilt a cube to move to the next letter in the alphabet or rotate it to spell a word. Stacking cubes to form short words can trigger audio feedback or animations, making spelling a tangible, interactive experience. Placing one cube on top of another could be used to compose compound words, such as "weekend." Flipping a cube might reveal alternate words or definitions, engaging students through multi-sensory feedback.

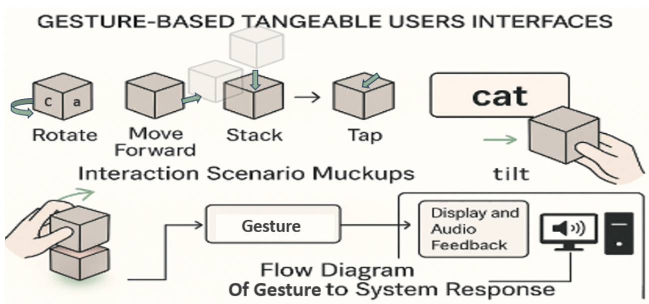


Fig. 2. early design sketch, mockup and flow diagrams

In addition to selecting AudioCubes as the CIT object for study, we emphasize the importance of gesture elicitation, understanding, and classifying the types of gestures performed by end-users. The classification can be checked against other references. For example, Sheridan et al.'s classification is defined as follows [10]:

Table 3. Sheridan et al.non-verbal dynamics of cubes

Action	Description	Events
Rotate	To turn a cube about an axis or center in a continuous, fluid motion exposing three sides of the cube at one time.	TURN + (exposed sides) + (speed)
Roll	Impelling cube forward by causing it to turn over and over on a surface.	TURN + (surface contact) SPIN + (surface contact)
Twist	To rotate cube while taking a curving path or direction using the wrist.	TURN + curve path
Turn	To cause cube to move around an axis or a centre.	TURN (right, left, up, down)

The study aims to structure existing knowledge on gestural interactions with a cubic user interface. A conceptual framework will be developed as a basis for future experimental validation. The next steps involve designing user studies to test and further refine the proposed framework. To achieve our objectives, we propose a research program that includes the following activities:

Task 1: Understanding CTI:

- Define and conceptualize the interaction space of CTI in general and within the context of learning environments.
- Explore the theoretical foundations and principles underlying CTI, including the group of cubic rotations. The cube group is the one having the largest order of symmetry.
- Investigate how gestures involved in CTI differ from other forms of gestures for tangible interaction, such as those listed in [12].
- Perform a Systematic Literature Review (SLR) on main digital libraries (e.g., ACM, IEEE, ScienceDirect) on references involving a cube as the main tangible user interface. Ensure description of each reference, comparison between them against criteria, and generation of new ideas based on the comparison. Use PRISMA method;

Task 2: Mastering the AudioCube technology:

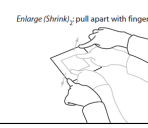
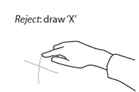
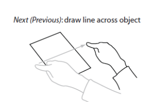
- Understand and describe a software architecture for managing interaction with an AudioCube. An AudioCubes is able to communicate via a MIDI interface. We therefore need to develop a framework for capturing the raw data sent by the AudioCubes via its MIDI interface, to apply gesture recognition algorithms, and to map the recognized gestures to high-level actions, such as those in the taxonomy.
- Develop and exploit MIDI interface and/or interface to acquire raw data from the device.
- Create new datasets and examples of usage.

Task 3: Fundamentals of Cubic Tangible Interaction: Instantiation to AudioCubes:

- Perform an initial Gesture Elicitation Study (GES – see [13] for a survey) involving 30 participants for simple Internet-of-Things actions. Identify an initial consensus set of gesture. See (4) an example of Gesture Elicitation Study (GES) conducted by Wobbrock, J. O., Morris, M. R., and Wilson, A. D. 2009 in their paper, "User-defined gestures for surface computing" [21].
- Consider the RepliGES framework [14] to create replications of the initial GES in new configurations [15], such as in different contexts of use, different set of referents, different sets of participants, perhaps different methods.
- Define and perform additional Gesture Elicitation Studies (GESs) [21] to consolidate the initial one and to determine how many new gestures emerge after each study to create a large-scale evolution model [30].

– Consolidate the results into a classification of CTI gestures. For each entry, give an identifier, a description, and a specification using the μGlyph notation [16]and studying its corresponding representation [17].
– Create a dictionary of cubic gestures with one cube(unimanual dominant or not), two cubes by the same user (bimanual symmetric or bimanual asymmetric), and four cubes hold by two users. Again use the μGlyph notation to define all configurations using the μDEX software (see `https://microglyph.imag.fr/`)

Table 4. Example of GES study: Gesture Agreement Wobbrock et al.(2009) [21]

Referent	**Most Common Gesture**	**Agreement Score**	**Gesture Type**	**User Rationale (Think-Aloud)**	**Illustration**
Move object	Drag with one finger	0.78	Physical	"Like dragging on a mouse."	
Zoom in	Pinch-out (two fingers)	0.65	Physical	"Spreading feels like stretching it."	
Delete	Draw "X" on object	0.52	Symbolic	"X means cancel or remove."	
Undo	Swipe left (two fingers)	0.38	Abstract	"Like going back in time."	

Task 4: Experimental studies of Cubic Tangible Interaction

– Define and conduct usability testing sessions where participants interact with the AudioCubes , mainly in the area of Learning.
– Collect qualitative and quantitative data on user interactions, feedback, and perceived usability.
– Analyse the data collected to provide a classification of the possible gestures and movements of the audio cube and identify common usability issues, user preferences and areas for improving the user immersion experience.

– Derive from these results implications for designing and developing CTI, based on AudioCubes.

The theoretical contributions and future work are outlined as shown in Figure 1, which provides a visual representation of the key concepts and directions for further research.

4 Conclusion

This research provides foundational insights into gestural interaction with cubic tangible interfaces (CTIs) in educational settings, establishing AudioCubes as a promising multimodal learning tool. The study examines how tangible cubes can support learning activities by identifying preferred gestures and movement patterns across various tasks and user contexts. It also explores user preferences and usage patterns. Developing a gesture classification framework and a proposed gesture dictionary is a significant step toward standardizing CTI design for broader usability. Additionally, the study emphasizes the importance of adapting interfaces for diverse users, particularly younger learners and individuals with different motor or cognitive abilities. Future work will refine this framework through extended empirical studies and seek to integrate CTIs more deeply into interactive educational environments to contribute to more inclusive and engaging learning experiences.

Acknowledgments. We acknowledge support from the EU EIC Pathfinder Awareness Inside challenge Symbiotik project (1 Oct. 2022-30 Sept. 2026) under Grant no. 101071147.

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