Objects-to-sense-with

Computational Tools for Embodied Spatial Learning

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This paper proposes objects-to-sense-with as tools that provide sensory-based learning of space and expand spatial knowledge beyond merely the formal and visual aspects currently dominant in design discourse. To reintroduce sensory-based learning methods in architecture education, this paper first revisits the sensory pedagogies formulated in the early 20th century, reviews precedents in the arts that utilize body-centered sensing technologies, and reframes previous discussions on the pedagogical role of technologies as tools for thinking. Finally, this paper describes the development of a wearable tool with embedded sensors created by the author and describes how the results are visualized. The developed tool, which is used to record sensory data in-situ by the user and allows for a body-centered representation of space, serves as an example of an object-to-sense-with that can be used to achieve a sensory-based and body-centered understanding of architecture.

Keywords: architecture education, design tools, sensor technologies, embodied perception

INTRODUCTION

Although physical spaces are being perceived and experienced through all the senses (Millar 2008), the design of spaces has been traditionally taught in architectural studios, usually focusing on formal visual qualities at the expense of the other senses, and separating spatial learning from the actual physical environment. A great number of studies in the field of environmental psychology have demonstrated the direct psychological response of the sensory aspects of space to those who occupy it (Gifford 2001). These studies however have only had a limited influence in the formal education of the architect. What learning tools and methods can we use today to turn design pedagogies into an active, situated exploration of physical spaces that incorporates all the senses?

This paper proposes the use of computation tools as "objects-to-sense-with" in the built environment which allow us to acquire embodied spatial knowledge. These tools, which take advantage of today’s self-tracking and sensing technologies, suggest methods inspired by Montessori’s and Moholy-Nagy’s sensory training exercises. Alluding to Seymour Paper’s "objects-to-think-with", objects-to-sense-with suggest an embodied pedagogical design approach that regards computational tools not as the educational end goal but as powerful tools for learning.
Precedents in education, arts and technologies that serve as a background for the proposed objects are first reviewed, then a description of a wearable computational tool developed by the author is provided as an example of an object-to-sense-with, and finally, possible scenarios of such tools in educational settings are being discussed.

EDUCATION OF THE SENSES
The focus on sensory training used by physicians such as Jean-Marc Gaspar Itard and Edouard Seguin in special education in the middle of the 19th and beginning of the 20th century, provided the background for Maria Montessori’s radical sensory pedagogies (Winzer 1993; Montessori 1912). The aim of the education of the senses as formulated by Montessori in the Montessori Method was "the refinement of the differential perception of stimuli by means of repeated exercises" (Montessori 1912, 173). In the Montessori Method, Maria Montessori describes techniques for the training of each of the senses, each of which involved a special set of didactic material, from sets of wooden blocks with different textures for training the sense of touch, to sets of bells for training the sense of sound.

According to Montessori, the isolation of the sense under study was an important parameter of sensory education. To train the sense of touch, children would be asked to discriminate between textures while blindfolded; to train the sense of sound, children would be asked to discriminate between sounds in the dark (Montessori 1912). In order to engage the students in a creative participatory sensory exploration of the environment, these sensory exercises would usually take the form of games. By extending children’s perceptual understanding through the sensory training exercises, Montessori aimed at equipping her students with refined aesthetic judgment. Montessori’s radical pedagogies were structured around auto-education methods, focused on learning through self-discovery and self-instruction. Her sensory training methods assume an auto-didactic exploration of one’s own physical surroundings through which an appreciation of the sensory qualities of the material environment can be achieved (Montessori 1912).

A few decades after the formulation of the education of the senses by Montessori, László Moholy-Nagy formulated sensory training methods for architects and designers while teaching in the Bauhaus school. According to Moholy-Nagy, the first-year education at the Bauhaus school aimed at broadening the sensory experiences of students and enriching their emotional values. Moholy-Nagy’s sensory training exercises, offering knowledge beyond textbooks and descriptions, helped in providing an experiential understanding of textures and tectonics (Moholy-Nagy 2005).

Like Maria Montessori, László Moholy-Nagy was concerned about providing the students with an understanding of the various different sensory qualities of material objects. Through sensory training exercises, students were able both to build a repertoire of different sensations and identify the subtle differences within the same sensation. The students' projects varied from tactile tables to a "luna-park for the fingers" to a "smell-o-meter." Such projects allowed students to study the senses by making tools to study and visualize them. Although the sensory assignments allowed students to measure the different sensations, the goal was not a scientific measurement and taxonomy of those but rather an experiential learning though creative experimentation (Moholy-Nagy 2005).

SELF-TRACKING FOR SELF-DIRECTED LEARNING
Sensing technologies that keep track of data related to their health, performance and mood allow people to self-monitor their behavior and empower them to take control over their actions through expanded self-awareness. In the Quantified Self movement, dedicated self-trackers collect, measure and analyze data about their behavior through phone applications, self-made tools and other tracking devices aimed at an empowered self. According to Gary
Woolf, co-founder of the Quantified Self movement, tracking data about one's own body and behavior is a way to take control of the data in a data-driven world and turn digital technologies into self-evaluation and self-discovery tools [2]. The automated digital tracking process allows for surprises in the learning process as it expands self-awareness beyond physical observation, revealing aspects about one's own self that would otherwise be unnoticed [3].

In a similar manner that proponents of the Quantified Self movement claim to gain a better awareness of their own bodies and behaviors, we might argue that tracking technologies could help us become more aware of our sensory responses to the built environment through the mapping of our sensory actions in space. In fact, artists have already taken advantage of such technologies to promote a body-centered awareness of the built environment. In his "Bio-Mapping" project, Christian Nold created a body-centered cartography of the city by superimposing people's paths and emotions on city maps. The bio-maps were made possible by asking participants to walk in the city while using a simple self-tracking device consisting of a biometric sensor and a GPS (Nold 2009). Another body-centered spatial project created through self-tracking was "Running Stich," by Jen Southern and Jen Hamilton. Running Stich was exhibited as a 5m x 5m projection of the multiple urban trajectories traced by different participants who used their GPS phone applications [1].

Such approaches point toward alternative geographies, mappings, and representation of the physical environment based on the emotions and the senses. If sensory education in the beginning of the 20th century was made possible by special sets of didactic materials and experimental studio prototypes, this paper suggests that by taking advantage of today's technologies we can propose novel tools and methods for the enrichment of the senses that not only render students aware of the material qualities of objects but also take the education of the senses out of the classroom, allowing for direct, experiential learning of the built environment in-situ.

FROM OBJECTS-TO-THINK-WITH TO OBJECTS-TO-SENSE-WITH
In his book Mindstorms, Seymour Papert (1993) used the term objects-to-think-with to refer to objects and technologies that act as tools for thinking, and particularly to stress the importance that computers can have in self-directed education. Papert broadly defines "objects-to-think-with" as "objects in which there is an intersection of cultural presence, embedded knowledge, and the possibility for personal identification" (Papert 1993, 11). In Mindstorms, Papert suggests that just as the gears he played with in childhood became his personal model for mathematics, computers could universally become objects-to-think-with for children in learning new concepts. Papert introduced the Turtle in the LOGO programming language in order to make the learning process in computers, as well as the learning process about computers, more tangible and concrete.

The LOGO Turtle moves on the screen following the user's typed instructions and gradually forms geometrical shapes by creating a line along her path. Children can identify with the Turtle, imagining themselves moving while she moves. As Papert argues, "Drawing a circle in a turtle geometry is body syntonic in that the circle is firmly related to children's sense of and knowledge about their own bodies" (Papert 1993, 63). In this way knowledge becomes active, situated, and self-directed. Children manage to acquire knowledge in a concrete and personalized manner, taking control of their learning. Papert uses Piaget's distinction between concrete and formal thinking, emphasizing the importance of concretizing abstract concepts. Whereas concrete thinking is embodied and occurs in an early developmental stage, formal thinking is an abstract form of thinking and occurs later in the development of the child.

Although Papert mostly refers to children's learning methods, both children and adults can benefit from body-centered, situated and active learning strategies. A great amount of literature in embodied cognition (Johnson 1990) and enactive cognition (Noe 2006) argues for body-centered knowledge
and embodied perception. Moreover, research in the cognition of space demonstrates that memory of spaces is mainly body-centric: people tend to recall spaces they have experienced relative to their bodily actions and movements (Papadopoulou 2015).

Alluding to Papert’s objects-to-think-with, the term objects-to-sense-with coined here refers to the use of objects that promote sensory-based learning by allowing knowledge to emerge through our bodily actions in the physical environment in a self-directed manner. Tools for architectural representation and documentation of space are traditionally focused on the built environment and material objects per se, excluding the body and the senses from the depiction of space. Using objects-to-sense-with to perceive and analyze space can lead to sensory-based architectural maps and drawings through the depiction of the interactions between the body, the built environment and the objects within.

As in the case of the LOGO Turtle, objects-to-sense-with can be body syntonic drawing tools that depict space based on one’s own paths, trajectories and bodily actions. Objects-to-sense-with are not tied with specific technologies or aesthetics. Rather, the term suggests a pedagogical role for computational tools in architecture and other the spatial disciplines focused on the senses and the physical exploration of the built environment.

THE DEVELOPMENT OF AN OBJECT-TO-SENSE-WITH

When visiting architectural spaces of interest, architects generally use photos, videos and quick hand sketches to capture and document the form and experience of space. Even though perspective drawings, images and videos express an experiential point of view of the building, they are usually based on visual experience, having limited reference to elements of the tactile, aural, olfactory and kinesthetic experience of space. Thus, the motivation behind the object-to-sense-with developed by the author was to suggest a tool that can offer multimodal body-centric documentation of spatial experiences. This multimodal documentation of spatial experience can allow architects and students to engage in a spatial discourse beyond mere formal aspects. The depiction and documentation of our bodily interactions with space can allow a discussion on experiential out-
comes of specific architectural solutions and comparisons between different architectural spaces on a sensory basis. Thus, built spaces could be analyzed based on possible trajectories of movement or on tactile or even olfactory responses. Although the same objects-to-sense-with could be used in various spaces by different people, each outcome would be unique since sensory-based documentation is always temporal, ephemeral and personal. Therefore, using objects-to-sense-with does not imply making objective measurements. Rather, it allows us to document experiential traces, suggesting new possibilities of interactions and motivating learning through personal exploration and discovery. Through the mapping of body-centric data, objects-to-sense-with can offer ways to render visible and tangible the unseen qualities of space and thus bring into the studios and the design discourse elements beyond the mere material aspects of built space.

The prototype developed by the author (Figure 1, Figure 3) is only an example of a possible object-to-sense-with. In an educational setting, students could build their own objects-to-sense-with and adjust the architecture of the tool to the sensory interactions they would like to focus on. As was the case in the sensory training methods used by Montessori and Moholy-Nagy, different sets of didactic material and different sensory training and mapping tools could be used for each sense or senses under study. In order to provide evidence that such a tool can be developed in an educational setting that does not require advanced hardware and software knowledge, simplicity in the technical implementation was an important parameter in the development of the tool.

In order to record and represent the sensory data in a simple manner, a set of sensors related to visual, tactile, auditory, kinesthetic sensory interactions were used and a simple set of rules to visualize the data (Figure 2). Sensory information that required complex implementation, such as information related olfactory sense, was not addressed. Moreover, environmental qualities such as temperature were not directly captured. Unless the space had a significant variance in the functions and indoor/outdoor uses, the temperature values would remain more or less the same. Thus, there would be no need for real-time, continuous tracking of the temperature data as there would be no significant variation in the values.

A simple two-dimensional sensory notation system was developed that could also be drawn manually, allowing for comparisons between the automated, software-generated sketch and the one drawn by the user. The prototype, which was designed as a wearable tool with embedded sensors, collects data regarding the position x,y of the user in space, as well as the sound and the tactile interactions of the user at each x,y position. Since the tool is continuously recording the data, when the data are inserted into the visualization software, the movement path of the person in space is gradually recreated as an animated graphical representation, together with a representation of the auditory and tactile interactions happening along the path.

By depicting each location of the person as a point in space, the trajectory of the person in space is finally visualized as a line. The time the person
spent at each x,y location is visualized by varying the
diameter of the points that compose the line of the
path. The tactile interactions are visualized as dia-
ogonal lines at each location, and the sound levels as cir-
cles with varying diameters, having as a center each
of the x, y locations that compose the final path (Fig-
ure 2, Figure 4, Figure 5). Two cameras, one added
to the wearable prototype, and one added as a head
equipment, complement the tracking setup to offer
additional information for processing regarding the
visual and tactile interactions.

Implementation
The prototype, which was 3d-printed in plastic, was
designed as a wearable tool that can be adjusted
to the user’s wrist. The microcontroller (Arduino
Uno R3) as well as the sensors were part of the de-
sign of the tool and were embedded in the proto-
type. The prototype also enclosed a camera to
record the materials the user interacted with through
touch. The following sensors were connected to
the microcontroller: An electret microphone, an in-
frared proximity sensor (VCNL4000), a triple axis mag-
netometer and accelerometer (LSM303DLMTR), and
a real-time clock. The microphone, proximity sen-
or and clock were embedded in the wrist-wearable
tool, whereas the triple axis magnetometer and ac-
celerometer were attached to a chest-strap that the
users wear in addition to the wrist-wearable tool (Fig-
ure 3).

The electret microphone was used to collect
information regarding the auditory interactions by
measuring the sound levels at each of the user’s lo-
cations throughout the user’s path in space. The in-
frared proximity sensor was used to collect informa-
tion regarding the tactile interactions. The proxim-
ity sensor was attached to a ring on the user’s finger
and was connected to the wrist-wearable tool. Since
the infrared proximity sensor provides information
regarding the distance of an object through the re-
lected infrared light, and the sensor is located at the
user’s finger, we can conclude that a small distance
value signals a tactile interaction with an object.

The values from the magnetometer and ac-
celerometer combined were used to calculate the
movement path of the user in space by providing in-
formation regarding the orientation of the user. The
magnetometer, which calculates the angle between
North and the device’s y axis, was used to provide
measurements regarding the position of the user.
The accelerometer was used to distinguish between
pause and movement and to compensate for the
magnetometer’s tilt. The real-time clock was used to
synchronize all different data when processing them.

All measurements were directly stored in an SD
card using a microcontroller SD card shield and were
imported afterwards as a text file into Processing soft-
ware. In the algorithm developed in Processing by
the author to visualize the user’s path, a 2D unit
vector is being created whose location is continu-
ously being updated according to the stored mea-
surements of the magnetometer and accelerometer.
Keeping the traces of the past 2D unit vectors, and
adding the newly instantiated vectors that represent
the more recent locations in time, a line is gradually
being traced on the screen that represents the path
of movement of the user of the tool exploring the
space.

Using the acceleration values, a threshold is de-
fined to distinguish between movement and pause
in the user’s path. When pause is detected, a circle
is drawn having as center the current location of the
unit vector, whose diameter varies according to the
duration of the pause. To visualize the auditory infor-
mation, for each new unit vector that is being instan-
tiated, signaling a new position of the user the space,
the sound level values captured at the given posi-
tion and time are mapped into the diameter of a cir-
cle having as center the location of the vector. Thus,
the larger the circles, the louder the sounds that were
captured at the specific location and time in space.

To visualize the tactile interaction in Processing,
a distance threshold is defined to determine whether
the touch condition is true or false depending on
the proximity of the objects detected through the IR
sensor. When a tactile interaction occurs, then a di-
agonal line, whose length can be adjusted to correspond to the proximity of the object, is drawn on the screen starting from the location of the 2D unit vector. The orientation of the line represents the direction of the action of touch in space, as it corresponds to the heading of the unit vector.

To filter information from the camera, a color matching algorithm was developed, which, through color recognition of the video frames, discerns the objects that were part of the longest in time tactile interactions with the user. The same color-matching mechanism was applied to video recordings that were captured by the camera close to the visual field of the user to detect the objects that were stared at the longest, and possibly most attracted the user’s visual attention. In both cases, the program takes a snapshot when the conditions that signify salient features are met. All features can be combined in a single interface embedding information regarding movement, sound, touch and vision.

In future development, the algorithm can be improved by taking into account the speed of movement. In the current state of development, only pause and movement are represented in the generated sketch, assuming that the person is moving at constant speed. By using the acceleration values, the speed of movement can be calculated as well, rendering more accurate the mapping of the movement path in space. Moreover, the use of a gyroscope could help distinguish between changes in the user's visual attention and movement.

Figure 3
The designed prototype as an Object-to-sense with and the sensors used to document sensory interactions in space.
orientation due to rotations of the body in the same location and changes of orientation due to walking in space.

**Scenarios of use**

An important aspect in the education of the senses as proposed by Montessori and Moholy-Nagy is the ability to focus on one of the senses by filtering out other sensory interactions. In the tactile and auditory training exercises they propose, students are usually blindfolded so that visual information does not interfere with the training of the other senses. Although being deprived of other senses so as to focus on a specific sense might be an appropriate method for small exercises in a studio setting, it would not be applicable in large setting or outdoor environments, since students would need to freely navigate. Therefore, it is suggested here that objects-to-sense-with can offer an alternative to traditional sensory isolation methods by allowing the users to filter their sensory interactions in space through the tool.

One way to filter the sensory information is to control how and which sensory data are being recorded. For example, users could adjust the hardware and software to output information regarding only touch, sound or movement, combinations of these, or all of these together. This flexibility would allow architecture students to study a built space through the lens of a specific sense. Moreover, in the interface where the data are being visualized stu-
Students can alternate between different channels of sensory information in a similar manner that they can add and subtract material information in a design interface by switching on and off layers of grouped objects. Superimposing the multimodal body-centered maps onto a building’s plans could provide insights on the experiential qualities of the space and body-centered ways to reflect on future designs.

A wearable tool for documenting our sensory interactions with the material environment can be a powerful learning tool, as it can take design education out of the classroom for in-situ spatial explorations. A common procedure in architecture studios is to review and analyze precedents as well as to visit and analyze the area of intervention. Instead of merely reviewing textbooks and documenting the site using videos, pictures and sketches, which mainly rely on visual means, object-to-sense-with would allow instead a multi-sensory situated learning method of studying both built spaces and their surrounded physical environment, offering a body-centered understanding and evaluation of architecture.

The object-to-sense-with tool allows users to focus their attention in specific modalities while exploring space, and thus provides a direct way of filtering sensory information. A physical exploration of spaces, that can be part of studio-based or other type of educational setting, can be focused on a specific sense in order to evaluate spatial qualities and experiences related to that sense. For example, if focused only on auditory qualities, the tool would motivate students not only to listen carefully to the environmental sounds but also to generate sounds in order to test the acoustic qualities of both the geometry of the space and the material used.

Visualizing the data collected from multiple sensory modalities allows body-centered drawings to be compared with conventional drawings of space as one can overlay or put side by side drawings of material boundaries of spaces and drawings of traces of bodily experiences of the same spaces. In other words, representing the data in a visual can allow architecture students to communicate ideas in the established media used so far in the studio and architecture practice which is drawings and sketches. If an educational setting allows for more experimental approaches, then one could imagine multisensory representations of space. For example, in the case of the developed tool, apart from a visualization of the sound levels, the recordings of the actual sounds can be embedded in the interface, allowing interactions in multiple modalities, and rendering more complete and accessible the provided information.

**CONTRIBUTIONS**

To provide a historical background for the development of alternative teaching methods in architecture that go beyond the formal and visual aspects of space and embrace all the senses, this paper offered a brief review of the sensory pedagogies formulated by Maria Montessori in the Montessori Method and introduced into design education by László Moholy-Nagy at the Bauhaus school. Reviewing the sensory pedagogies of the early 20th century allowed us to rethink the methods used in current educational models in the design studio and formulate methods for a multisensory learning of space.

Dedicated self-trackers utilize tracking technologies to gain a better awareness of their bodily needs and behaviors, and artists utilize GPS and other
tracking devices to map urban space from a body-centered perspective. Briefly reviewing precedents in the arts and the aims of current self-tracking tendencies, the author proposed the incorporation of such approaches in design education to suggest tools for sensory pedagogies, reframing the pedagogical methods proposed in the early 20th century.

Seymour Papert used the term objects-to-think-with to refer to technological tools that act as tools for thinking, enabling students to acquire concrete knowledge through a body syntonic, self-directed learning. Building upon Papert’s terminology, while stressing the sensory aspect of embodied knowledge and the use of sensing technologies, the author coined the term objects-to-sense-with to propose a pedagogical role for sensory-tracking tools and offer a response to the need of sensory-based, body-centered learning in the architecture.

The author developed a wearable tool as an example of an object-to-sense-with, demonstrated the results and discussed scenarios of use and possibilities for further development. The tool functions as a generator of simple body-centric diagrams of space that can be used to compare and contrast different sensory interactions in the same space or the sensory interactions of the same person in different spaces. Through gathering real-time data regarding the users' location in space, their tactile interactions and the sound levels relative to their position in space, and by visualizing the data in Processing, users are able to document their real-time body-space interactions in the physical spaces they explore.

Objects-to-sense-with can be used in architecture to offer in-situ exploration of the built environment that focuses on the senses. Different possibilities can be explored for representing space in multisensory and multimodal means through the recorded data, and different scenarios can be employed to engage students in sensory-based learning of space by allowing them to make and use their own objects-to-sense-with as tools for self-directed, body-centered learning.

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