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The Use of 3D Printing in Comparative Research and Teaching

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The past decade has witnessed remarkable advancements in 3D printing. Surprisingly, few comparative psychologists have taken advantage of 3D printing in the design of apparatus. Our paper discusses the advantages of 3D printing and offers practical suggestions on how engineers and comparative psychologists can communicate with each other on apparatus design issues. Moreover, we discuss how apparatus design with 3D printing can increase student interest in STEM. We first document that comparative/experimental psychologists seldom use 3D printer technology and then offer recommendations on how to increase the use of such technology in the behavioral sciences.

Keywords: 3D printing, additive manufacturing, behavioral apparatus, behavioral research, comparative psychology

A major goal of psychology is to explore abilities across species. One issue hindering these comparisons is the lack of standardized apparatuses. An example of standardized, commercially available apparatuses for behavioral experiments are Skinner boxes, shuttle boxes, and mazes that typically cost between \$2,000-\$5,000 and are restricted to commonly used animals such as chimpanzees (and other non-human primates), mice, pigeons, rats, and fish. The lack of standardization has contributed to the general perception that many findings in psychology are not replicable (Grice et al., 2012; O. S. Collaboration, 2012). The goal of the present paper is to help stimulate the interactions between engineers and comparative psychologists in the area of 3D printing.

In our experience, students receive little training in the design of behavioral apparatuses. There is an old adage familiar to previous generations of comparative psychologists where “the best way to know your animal is to design an apparatus to study its behavior.” Therefore, a secondary goal of this paper is to encourage students to learn how to design and print apparatuses.

Three-dimensional (3D) printing technology, also known as additive manufacturing, is making a big leap in all commercial and educational sectors. This trend is primarily due to its unique capability to produce parts in layer-by-layer fashion directly from the digital 3D model. 3D printing offers immense versatility in terms of design complexity. A wide range of materials can be used, giving the researcher an almost unmatched selection of platforms to choose from (polymers, composite, metals, ceramics, glass, and edibles). 3D printing significantly reduces energy usage by using less material and eliminating steps in the production process. Moreover, no additional tooling is required; parts can be produced with minimal material loss. These characteristics enable the creation of 3D apparatuses that may be lighter, stronger, multicolor, and multi-material.

This paper was stimulated by anecdotal evidence gathered by the authors that few comparative/experimental psychologists utilize 3D printing in their research and teaching. The senior author (CIA) has over 30 years of experience in comparative psychology and has been developing apparatuses for various organisms throughout his career. The use of 3D printing is a natural progression in the construction of apparatuses, yet surprisingly few comparative psychologists are taking advantage of these remarkable devices. Thus, the purpose of this paper is two-fold. First, we wanted to estimate the use of 3D printing by comparative/experimental psychologists and, second, to offer recommendations on how to increase the interactions between engineering departments and comparative psychologists in the area of 3D printing.

The use of 3D printing is highly recommended for comparative psychologists. First, the cost of commercial behavioral apparatuses can run into thousands of dollars for a simple “Skinner Box.” Second, as grant money and start-up funds for young (and older) faculty are becoming increasingly difficult to obtain, 3D printers allow faculty members to spend significantly less on apparatus costs. Third, for those comparative psychologists wishing to work with more exotic laboratory species, such as invertebrates, there are few commercially available apparatuses. In such cases, the comparative psychologist must construct an apparatus on their own, which can be time-consuming and often of low quality and limited applications. The inferior quality of many of these “handmade” apparatuses induces experimental errors that influence the experimental results and replicability. A good example of the lack of commercially available apparatuses for invertebrates is the training device for planarians known as “Train-a-Tray.” Train-a-Tray was a commercially available device for training flatworms discontinued at least a decade ago. With 3D printing, we can reproduce the apparatus. Fourth, by having an ability to print 3D apparatuses, it extends comparative psychology to a wider range of individuals. For example, high school students and college undergraduates can now develop sophisticated apparatuses to study a wide range of behavioral issues. Fifth, 3D printing of behavioral apparatuses will lead to greater standardization of apparatuses and greater standardization among behavioral laboratories. The latter point should not be underestimated. With few exceptions, apparatuses in the behavioral sciences are not standardized (Scheiner, et al., 2013; Sidowski, 1966). Sixth, 3D printing is not just for the development of behavioral apparatus, it can be used to create artificial limbs for animals. We may not be voicing the popular opinion, but, in our view, there is no group of scientists better qualified to assist in the creation of artificial limbs than comparative psychologists.

Use of 3D Printing In Comparative Psychology

To document the use of 3D printing in comparative/experimental psychology, we surveyed the methods section of each article in the *Journal of Comparative Psychology* (JCP), the *International Journal of Comparative Psychology* (IJCP), and the *Journal of Experimental Psychology: Animal Behavior Processes* (JEP) from 2001-2020. The rationale behind the selection of these journals is that they focus on the study of animal behavior, which we believe has the greatest opportunity to incorporate 3D printed apparatus. To capture the use of 3D printing in other areas of psychology, we also conducted a review of articles in the journal *Behavioral Methods, Instruments, and Computers* (BMIC) for the same 20-year period. The latter is the only psychology journal that specializes in technique.

Results

Our results were astonishing. Table 1 shows the number of articles appearing in the four journals surveyed. The total number of articles we reviewed were 4,341. Table 2 shows that of the 4,341 articles surveyed, only one used 3D printer technology, and that article was ours (Dinges et al., 2017).

Table 1

Number of Total Articles for a 20-year Period

Years	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
JCP	50	53	50	47	49	53	48	52	50	49	50	47	49	49	44	44	38	48	55	11
IJCP	20	21	16	22	31	25	28	7	16	40	25	18	25	39	33	25	33	39	22	3
JEP	30	34	27	27	45	49	42	40	53	47	50	43	38	41	39	38	33	33	34	7
BMIC	70	71	75	83	80	88	121	129	142	114	105	97	112	97	108	126	163	179	179	28

Table 2

Number of Total Articles using 3D Printing in Research

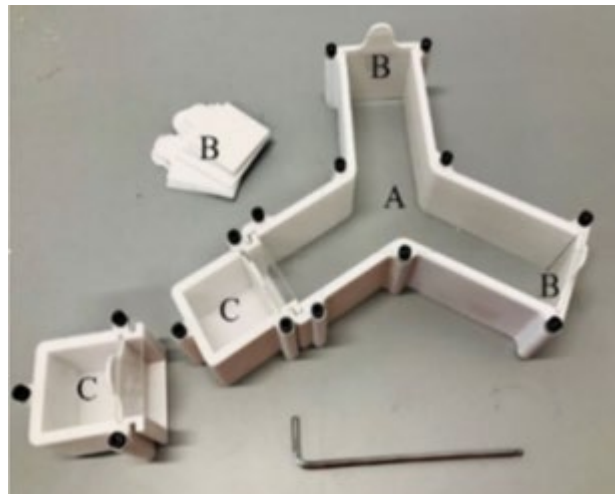
Years	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
JCP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IJCP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JEP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
BMIC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Case Study

In one investigation, the authors used a 3D printed apparatus (Y-Maze) to estimate avoidance and foraging behavior in response to increases in magnetic fields. In the appendix to that paper, we provide the schematics to reproduce our maze (Chicas-Mosier et al., 2020).

Figure 1

Diagram of the Y-maze



Note. A is the 3D-printed maze, B are the removable color panels, and C is the bee containment box.

Previously, these kind of experiments were performed with a handmade apparatus usually constructed from cardboard, plastic, or wood. This type of apparatus is nonstandardized and severely lacking in replicability. Our 3D printed Y-maze contained a clear Plexiglas cover and base to easily see the honey bee's

movement (Figure 1A). A commercially available 3D printer (CraftBot) utilizes the fused deposition modeling (FDM) technology to additively manufacture the Y-maze with white color polylactic acid (PLA) polymeric material, removable color panels, and a bee containment box. The 3D printing was performed using a 0.4 mm diameter steel nozzle and 1.75mm filament of PLA material with the optimal printing parameters for PLA filament materials (extruder and bed temperature are 220°C and 60°C, respectively). The clear plexiglass cover was cut to size using a CO₂ laser. The maze consisted of three arms: a start box with no choice variable (Figure 1C) and two choice arms that terminated with a removable colored panel (Figure 1B). Panels were painted with Testor's paint in either yellow or blue. It is important to note that it is not always easy to paint plastic. It may require a primer or a paint that contains a primer.

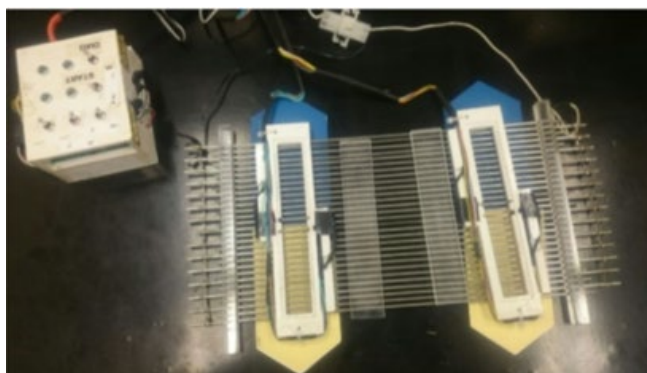
Each bee was captured from a 20% aqueous sucrose feeder and brought to a nearby indoor laboratory facility 12.4 km from the apiary. A 1:2 mixture of honey:sucrose was provided to bees after removal from the feeder until transfer to the start box (Figure 1C). Upon arrival to the laboratory, bees selected for immediate use were transferred to a 3D-printed box (Figure 1C) and held for 10 minutes. The rationale for placing the bee in the holding area (Figure 1C) was to allow the insect a period of adaption and reduce post-handling stress variables. Further handling was avoided after the adjustment period. Magnetic field disks were attached vertically behind panels B at the end of both choice lanes, and painted sucrose wells were placed at the base of the end of the two choice arms (Figure 1B). The inside walls of each well were painted with the corresponding color of the panel at the end of these arms (Figure 1B). Both wells contained 200 µL of 1M sucrose for use throughout the experiment.

Magnetic field strength directly above each well was tested before each experiment. Each experiment included two honeybees. Boxes (Figure 1C) containing each bee were labelled accordingly. To start each trial, the box containing a bee was docked at the start box (Figure 1C), the start gate was opened simultaneously with the start of a 5-min timer. After 5 min, the experimental bee was coaxed back into the start box (Figure 1C) with minimal handling, and the start box (Figure 1C) was replaced with the other bee-box, allowing a 5-min rest period for each bee between trials. Bees were recorded from above for the entirety of the experiment (10 total trials per bee). Videos were later coded for total amount of time spent per choice lane and amount of time spent drinking. The results indicated that low strength magnetic fields can serve as discriminative stimuli, but honey bees prefer to use prior experience in foraging tasks. While the maze may seem simple, the discussions between engineers who designed and printed the apparatus and experimental psychologists who provided parameters of the maze taught all of us a lesson on how to communicate between the two disciplines.

As another example, Figure 2 shows an early model of a 3D-printed shuttle box for honey bees. This apparatus was used for several publications, and, by using 3D printing, we can easily refine the apparatus. The box in the upper left corner is a low-cost experimental controller that presents experimental conditions and records data automatically (Varnon & Abramson, 2013, 2018).

Figure 2

Image of the Shuttle Box Apparatus



Note. The controller is in the upper left corner.

Questions

This paper brings together two ideas not previously considered as complementary. To encourage discussion and conversation between engineers, comparative/experimental psychologists, and students, we recommend that the questions below serve as the basis for dialogue. These questions were developed based on the experiences of the authors. We recommend that before printing a 3D apparatus, the developer should contact someone familiar with the operation of 3D printers. Many of these individuals are in engineering departments.

Question 1. What is the Purpose of the Apparatus?

What do you intend to study with the apparatus? Will the apparatus be multipurpose? An apparatus designed to study locomotion, such as a behavioral arena or running wheel, will generally present less design issues than a shuttle box or operant chamber. However, with the addition of more features, both the running wheel and the behavioral arena can be used for learning and other types of experiments. We recommend that apparatus design be part of a unit within a comparative psychology course. Within this unit, students gain experience designing apparatuses and, with the addition of a guest lecturer (such as an engineer versed in 3D printing), will learn how to express their ideas in a way that engineers can understand. Conversely, the guest lecturer will better understand the nuances associated with the design of behavioral apparatuses.

Question 2. What is the Species to be Used (Aquatic, Flying, Crawling, etc.)?

Will the species be conventional, such as the rat or pigeon, or be as unconventional as the horse, the crab, or beluga whale? Each species brings their own unique design issues and presents the student and researcher with a unique and interesting set of problems. For example, about 40 years ago, the senior author ran rats in running wheels often using aversive stimulation. The problem was that after two or three sessions, it was difficult not only to place the rat in the apparatus but also to extract the rat from the apparatus without being bitten. The problem was that the design of the door did not permit easy extraction. Another problem was that the running wheel was not easily cleaned, thereby leaving chemical cues that could influence the performance of the next subject. When the senior author had the opportunity to build running wheels for earthworms and honey bees, these lessons were remembered (Abramson, 1994).

Question 3. What Materials should be used in the Design of the Apparatus?

As a behavioral scientist might be unfamiliar with the type of materials used by 3D printers, the engineering student/consultant must have a knowledge of materials used for various printers and the type of printers. By possessing such knowledge, the engineering student/consultant would be in a better position to advise the developer. For example, when making a shock grid for an insect, the surface must be designed in a way that when fluids from the insect touch the grid, the grid will not short out. As another example, while as a graduate student, the senior author would often run down to the laboratory machine shop with an idea for an apparatus. While the director of the machine shop would patiently listen to him, the director would point out the many problems with materials and designs – the apparatus could not be built as the senior author had originally designed it. If the director did not have such knowledge, much time and expense would have been wasted on an apparatus that would not have worked as intended.

Question 4. How is the Behavior in the Apparatus to be Measured (i.e., Placement of Sensors, and What Type of Sensors)?

During the design phase of the apparatus, the engineering student/consultant must have knowledge of the sensors used to record the behavior and what type of sensors should be used. For example, only infrared sensors can be used for honey bees, as other types of light-based sensors may unconditionally attract the bee to the vicinity of the sensors. Moreover, where should they be placed? If a honey bee is used in a shuttle box/choice chamber, where should the sensors be placed? Should there only be one sensor traversing the

midline of the apparatus? Alternatively, should two sensors be placed slightly off the midline so that if the honey bee crosses the midline, it is actually known to be in a particular compartment of the apparatus? An interesting sensor problem occurred in Turkey when the sensors detecting a honey bee would not turn off. After much effort to fix the problem, it was discovered that, while the sensors worked well in the United States, the fluorescent lightbulbs in Turkey emitted a frequency that activated the sensors (Dinges et al., 2013).

Question 5. Where to Place Stimulus Cues and What Type of Stimulus Cues can be Used?

A related issue to the type and placement of recording sensors is where to place cues and what type of cues should be used. For example, if olfactory cues are used, how should they enter the apparatus? How are the olfactory cues removed? What is the interaction between the olfactory stimuli and the type of material used to print the apparatus? As a second example, while many behavioral apparatuses do not vary the texture of the substrate, if different textures are required (e.g., as discriminative stimuli), this must thoroughly be discussed. If a different type of 3D printer is used to produce the substrates, this may introduce some inconsistencies when the apparatus is printed. It is also worth noting that if visual cues are used, then they must be appropriate for the organism under investigation in terms of both wavelength, shape, and size. In regards to the shape and size, as an undergraduate teaching assistant in an experimental psychology course, the senior author observed students performing a simple runway experiment with rats. The students were frustrated because their rats could not discriminate between a triangle and square even after 30 trials. The answer to their problem was simple, they made the triangle and square so large that their rats could not see the forest through the trees.

Question 6. How is the Apparatus to be Connected to the Control Equipment?

How is the apparatus that is connected to the control equipment necessary for the automated presentation of stimuli and the recording of responses? If this issue is not discussed during the design phase, the developer runs the risk of needing extra space to accommodate all the wires and connections to automate the apparatus. As anyone familiar with the relay racks of past generations can attest to, the amount of connections can be a daunting challenge if they must be traced, modified, and/or reconnected.

Recommendations

The results of our survey show that few behavioral scientists in psychology utilize 3D printers. This is true both within and between the journals we selected to survey. We are aware that some institutions only recently have begun to develop 3D printer facilities. Nevertheless, it is somewhat disappointing that, over the two decades, there was no significant increase in the use of 3D printer technology. The authors of this paper represent the fields of engineering and comparative psychology, respectively, and believe our experience working together can serve as a potential model to increase the use of 3D printers in comparative psychology. We offer the following recommendation:

1. Apply to the National Science Foundation (NSF) for funds to support 3D printing workshops. The NSF and other granting agencies often have funds to support such workshops. State agencies may have grant funds as well.
2. Develop an undergraduate/graduate course, such as “3D Printing for Experimenters.” Such a course would stimulate collaboration between psychologists and engineers, improve communication between the two fields, and teach students vitally important skills related to apparatus design.
3. Create a library of schematics for 3D printed apparatuses. This library would be open access and help standardize apparatuses across various laboratories.
4. Assist laboratories in developing countries who cannot afford behavioral apparatuses. For example, we have designed, printed, and distributed various 3D apparatuses to educational institutions in Africa, Brazil, Egypt, Iran, and the U.S. Territory of Puerto Rico.

5. Submit summer-camp grants focused on 3D printing for high school students. Under the dual supervision of an engineer and comparative psychologist, students can develop behavioral apparatuses that can be used at their home institutions and/or home school. It has been our experience that 3D printing is a wonderful way for students to become interested in STEM and has the added benefit of encouraging students to understand the more natural science portions of psychology. It also increases a student's observation and critical thinking skills, as there is no better way of knowing your animal than to design an apparatus to study its behavior.

In short, these questions are important for both the education of comparative psychology students and engineering students, as we expect that, over the coming years, there will be a greater interaction between behavioral scientists and engineers.

Discussion

The paper provides a compelling call to action to increase connections/collaborations between engineers and comparative psychologists. It also calls for comparative psychologists and students to learn how to use and incorporate 3D printers into their research and teaching. In the course of such collaboration, both comparative and engineering students would benefit by being exposed to a new area of research/technology. We believe that students would be especially challenged as they would be faced with solving unique design problems.

Our article is the first we know of that attempt to reach out to comparative psychologists and their students regarding the advantages of 3D printing. Despite the many advantages of 3D printing behavioral apparatuses, our results showed that few researchers in the behavioral sciences utilize 3D printing. In some ways, this should not be a surprise, as few students in psychology and perhaps other behavioral sciences learn how to construct apparatus (Varnon et al., 2018). The laboratory of the senior author is one of the few where students learn how to construct apparatuses for a variety of organisms. 3D printing can lead to better interactions between engineers and comparative psychologists, produced standardized techniques that are needed in the behavioral sciences, and encourage skills which may encourage students to enter the STEM aspects of psychology.

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