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Automated Research in Comparative Psychology: Limitations and New Directions

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Behavioral research is often enhanced by automated techniques, where experimental parameters and detection of behavior are controlled by electromechanical systems. Automated research promotes refinements in measurement, greater experimental control, longer durations of data collection, reduction of observer fatigue, and may permit new types of research to be conducted. In comparative psychology, use of automated techniques are often restricted to popular model organisms of fields such as behavior analysis and behavioral neuroscience. One factor contributing to this species-restriction may be the availability of automated research equipment, as most commercial research equipment is designed for rodents, and many researchers lack the skills required to create their own automated equipment. However, there are alternatives to commercial equipment, as some behavioral scientists have made available their own species-flexible, low-cost research equipment. In this paper, we provide three reviews. We first review recent trends in automated comparative psychology research, and then relate this to a second review on currently available automated research equipment. We also review affordable alternatives to commercial equipment that have been designed by behavioral scientists. Finally, we discuss useful technological skills that may allow comparative psychologists to take automation into their own hands and design equipment specific to their species and research topic.

One major goal of comparative psychology is to explore behavioral and cognitive abilities across species. Owing to a number of important historical figures, including Aristotle, Charles Darwin, Nikolaas Tinbergen, and B. F. Skinner (Burghardt, 2009; Dewsbury, 1984; Jaynes, 1969; Lockard, 1971; Papini, 2003), comparative psychology has collected many methods and paradigms needed to make such comparisons. More recently, comparative research has been enhanced by use of automated procedures, in which recording behavioral variables and environmental manipulation is controlled by an electromechanical system. Ferster and Skinner's (1957) research in behavior analysis is one early example that demonstrated the usefulness of automated apparatuses, and subsequently inspired researchers across fields to make use of automation. For some reviews of the history of instrumentation in various aspects of psychological research see Abramson, (1994), Escobar (2014), and Sidowski (1996).

Automated techniques can provide several advantages compared to non-automated research: a wider swath of behavior can be measured simultaneously for any given organism, the duration of each measurement period can be extended indefinitely without concern for observer fatigue, and judgment errors can be better accounted for. As an example of the latter, in human research, environmental changes (e.g., Harris & Ciminero, 1978), behavioral patterns (e.g., Mash & Makohoniuk, 1975), and a host of other considerations adjust how we perceive behavior (see Kazdin, 1977 for a review), and it is likely these same issues occur across taxa. In addition to laboratory use, automation can also be used in the field to provide these powerful measurement

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benefits while still maintaining ecological validity (e.g., Craig et al., 2012; Morand-Ferron, Hamblin, Cole, Aplin, & Quinn, 2015).

Unfortunately, comparative psychology has often struggled to maintain a truly comparative focus (Burghardt, 2006), and this may be especially true for automated research as equipment is often available for only the most popular species. An additional barrier for automated comparative research is the high costs of commercial research equipment (Devarakonda, Nyguyen, & Kravitz, 2015; Hoffman, Song, & Tuttle, 2007; Pineño, 2014; Varnon & Abramson, 2013). However, a new researcher-driven movement in low-cost automation has permitted many laboratories to move away from reliance on commercial equipment. This may be the start of a new direction for truly comparative automated research. In this paper, we provide three reviews to investigate these topics. We first review current trends in species use and automation in comparative psychology. We then review currently available commercial research equipment and discuss how this may affect trends in comparative research. We also review low-cost alternatives to commercial equipment, and discuss how they may provide new opportunities for research in comparative psychology.

Review 1: Species and Automation in Comparative Psychology

The comparative nature of the field suggests that a wide, balanced variety of species should be studied. However, early comparative psychologists instead found that rats were becoming a dominant research subject. By the 1920s, rats had become increasingly popular subjects with a variety of animal psychologists (Dewsbury, 1984; Logan, 1999). This infestation of rats continued into the 1980s, and was noted in journals such as *Animal Behavior* (Lown, 1975), and the *Journal of Comparative Psychology* (Gallup, 1989). From 1990 to 2004, the number of studies using rats in the *Journal of Comparative Psychology* dropped sharply, only to be replaced by non-human primates (Burghardt, 2006). Birds were consistently studied but the number of experiments involving reptiles, amphibians, fish, and invertebrates were very limited.

Many have voiced concern about the limited comparative perspective in comparative psychology. Critics have claimed that comparative psychology scientifically limits itself by focusing on a small proportion of species (Lockhard, 1971). This issue is so important that the most recent two editors of the *Journal of Comparative Psychology*, Josep Call and Gordon Burghardt, have both drawn attention to this problem. Josep Call suggested that a narrow set of subjects hinders our ability to reconstruct evolutionary paths for cognitive traits (Price, 2010), while Gordon Burghardt, stated that without information derived from a wide range of species we will have a “barren understanding of our own species” (Dingfelder, 2004, p. 51).

Method

To see if concerns of species use are still valid in recent years, we continued Gallup’s (1989) and Burghardt’s (2006) reviews of species use, and extended them to include both major comparative psychology journals, the *International Journal of Comparative Psychology*, and the *Journal of Comparative Psychology*. We further extended these reviews by also recording if the experiment used automated procedures. Our analysis focused on the years 2000 to 2016, and excluded editorials, theoretical papers, review papers, purely physiological research (e.g., body dimensions, facial features, heart rate, etc.), and human experiments. For each article, we recorded the details for each experiment separately, given that experiments in an article may differ substantially. We also recorded each species used in an article separately. All articles were manually accessed via institutional databases and publication websites, and then each experiment within each article was manually checked for inclusion by the second author. A random correspondence check was conducted to ensure accuracy of data. A total of 1,912 experiments, across 1,213 articles, were analyzed.

For each experiment, we recorded if hardware and/or software was used to automatically recorded behavior, or manipulate environmental variables. Experimental apparatuses were classified as *manual* if no forms of automation were used, or if the experimenters were required to actively moderate independent variables (e.g., presenting stimuli, controlling each putative reinforcer delivery with a button), and/or record dependent variables (e.g., pointing microphones, counting audio patterns, coding behaviors post-hoc via audio or video record). Automated experiments were classified experiments as *partially-automated* (i.e., either the independent or dependent variables were automated) or *fully-automated* (i.e., both the independent and dependent variables were automated). For automated experiments, all automated measures and procedures were recorded. We excluded articles from the review if the authors did not clarify necessary details about the species, procedures, independent variable(s), or dependent variable(s).

Results and Discussion

Figure 1 displays the use of automation across the included articles. Between 2000 and 2016, we observed 1,470 manual apparatuses, 99 partially-automated apparatuses, and 326 fully-automated apparatuses. The number of partially-automated apparatuses may be slightly over-estimated given that this analysis required articles to specify automation in their methods; articles lacking sufficient details to classify as fully-automated were instead classified as partially-automated. The total use of automated apparatuses from 2000 to 2016 is small (23.12% of surveyed articles), and the rate appears to be stable across this period.

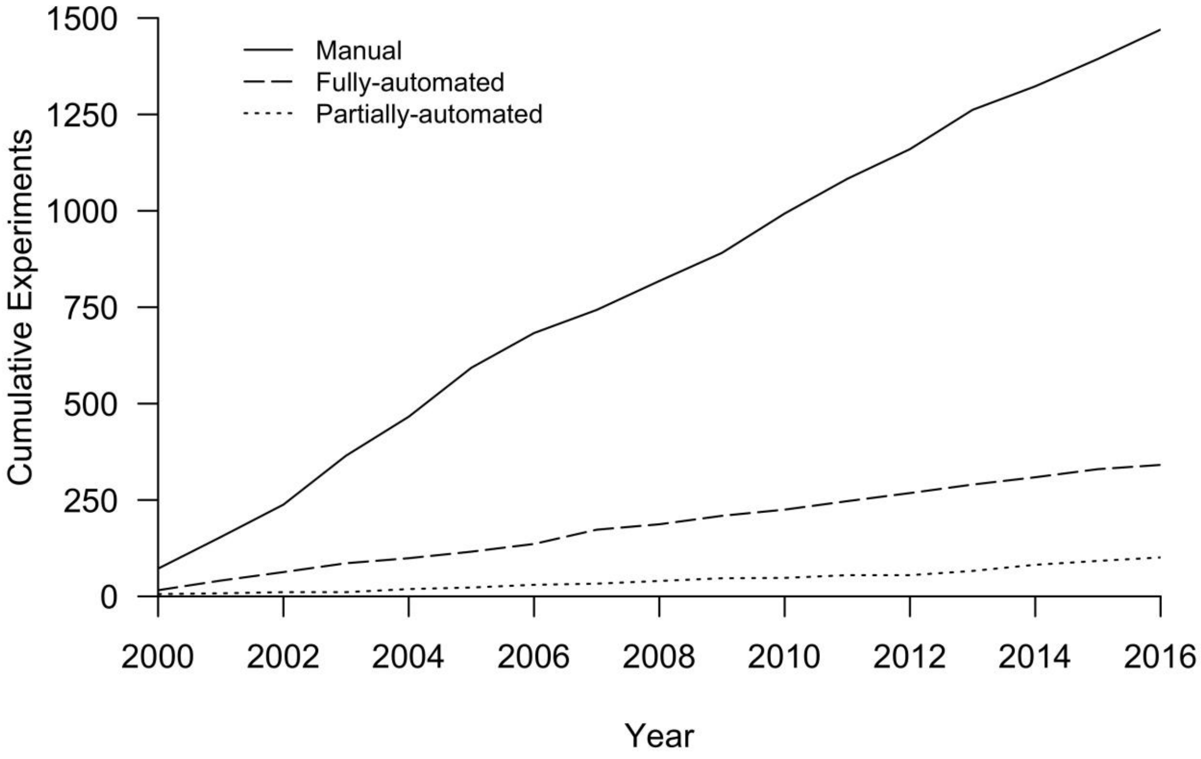

Figure 1. **A cumulative graph of automation in comparative psychology.** The plot shows manual, partially-automated, and fully-automated apparatuses used in experiments found in the *International Journal of Comparative Psychology* and the *Journal of Comparative Psychology* from 2000-2016.

Figure 2 displays a phylogram and stacked bar plot of species included in 10 or more experiments, both manual and automated, organized by phylogenetic order, then class. The phylogram was created in R Studio® (RStudio Team, 2015) with the "ape" and "taxize" libraries (code available upon request). The listed

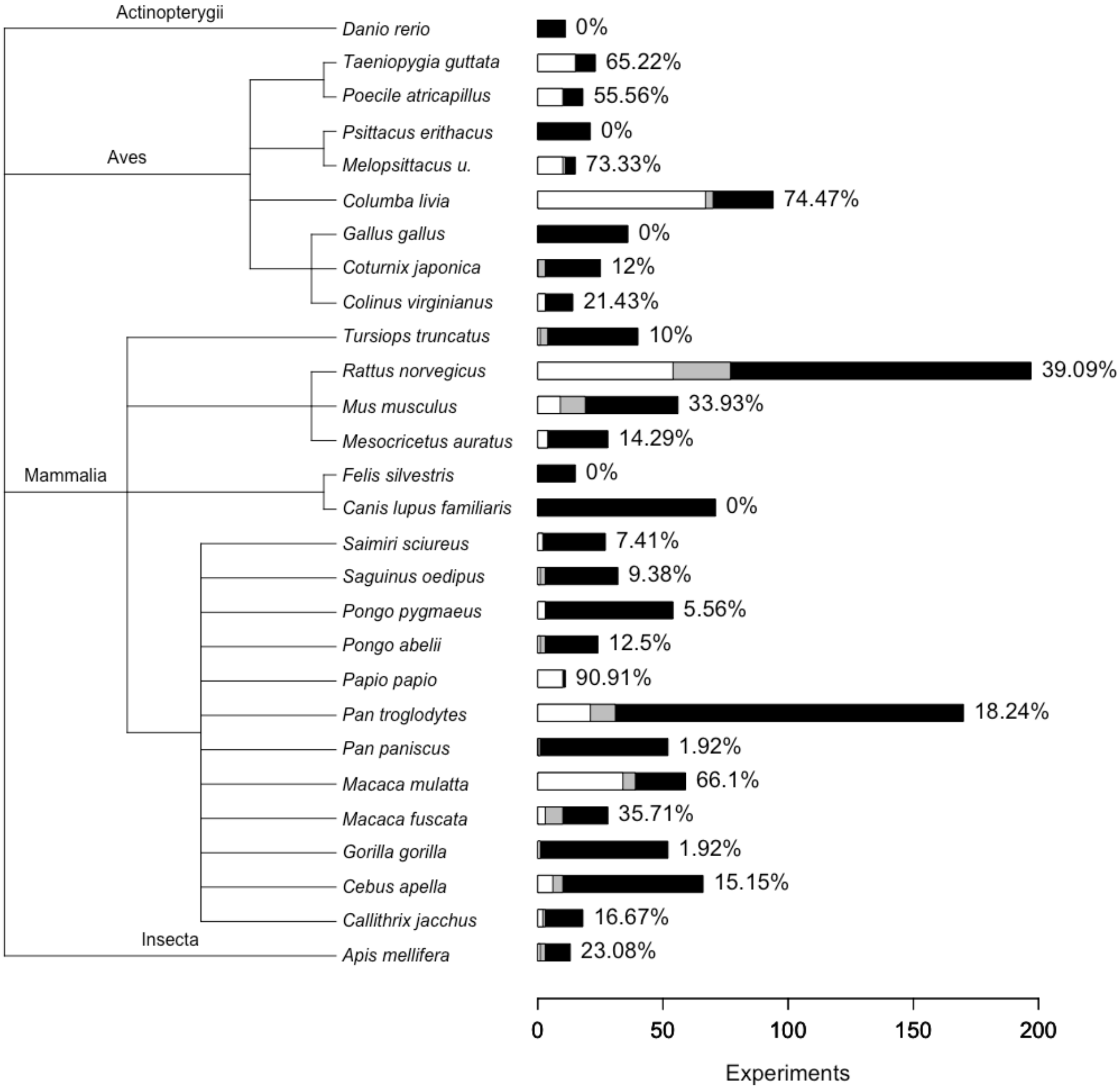

Figure 2. **A phylogram and stacked bar plot displaying species observed in 10 or more experiments in the *International Journal of Comparative Psychology* and the *Journal of Comparative Psychology* from 2000-2016.** Black-shaded portions of the bar plot represent experiments with manual apparatuses, grey-shaded portions represent partially-automated apparatuses, and white-shaded portions represent fully-automated apparatuses. The percentage beside each bar plot shows the percent of experiments that were automated (partial or full automation).

species represent 66.4% of the total species captured with this analysis. Rats (*Rattus norvegicus, n* = 197), chimpanzees (*Pan troglodytes, n* = 170), and pigeons (*Columba livia*, *n* = 94) were the most frequently observed species. Of all orders, primates were most frequently presented (*n* = 440), while zebra fish (*Danio rerio, n* = 11) and honey bees (*Apis mellifera, n* = 13) were the only species representing non-mammalian and non-avian taxa. Automation (partial or full) was the most common with rats (*n* = 77), pigeons (*n* = 70), rhesus macaques (*Macaca mulatta*, *n* = 39), chimpanzees (*n* = 31), and mice (*Mus musculus*, *n* = 19) while full automation was the most common with pigeons (*n* = 67), rats (*n* = 54), rhesus macaques (*n* = 34), chimpanzees (*n* = 21), and zebra finches (*Taeniopygia guttata, n* = 15). Overall, automation (partial or full) was used in 57 of the 280 listed species, which indicates that automated procedures are used less frequently than manual techniques.

We also noted some differences between the journals. *The Journal of Comparative Psychology* had more total experiments (1,521), more species represented (225), and more partially- or fully-automated experiments (312) than the *International Journal of Comparative Psychology* (391 experiments, 89 species, 113 automated experiments). However, the *International Journal of Comparative Psychology* had a higher proportion of species (22.76%) and automated experiments (28.90%) per total experiment than the *Journal of Comparative Psychology* (14.79% species, 20.5% automated).

Table 1 shows the behavioral responses that were recorded in three or more automated experiments, sorted by frequency and species. Pecking (*n* = 91) was the most commonly observed response, and was seen primarily in pigeons. Lever pressing (*n* = 48) was the second most commonly observed response, and was seen primarily in rats. Joystick moving (*n* = 39) and touch screen use (*n* = 24) were the next most commonly observed responses, and were primarily observed in primates.

The results of our review on species use (both manual and automated) mirror the findings of Burghardt's (2006) review and show that the field is still relatively dominated by non-human primate research, though rat research is experiencing a resurgence. Overall, the lack of diversity in observed taxa demonstrates that the comparative literature continues to research a uniform conglomeration of species. As seen in previous reviews (Burghardt, 2006; Gallup, 1989), very few experiments were published involving reptiles, amphibians, fish, and invertebrates. Our review also found that automation was uncommon outside of a small number of taxa (rodents, pigeons, and primates), and given the potential benefits of automation, this might hinder our comparative understanding of behavior. The use of a limited selection of species in automated research might be caused, in part, by the available automated instruments offered by behavior research companies. This last concern is the topic of our next review.

Table 1

Behaviors Recorded in Three or More Automated Experiments

Behavior	**Frequency**	**Species**
Calls	7	*Rattus norvegicus*
Calls	6	*Hyla versicolor*
Head bobbing	6	*Zalophus californianus*
Heart rate	4	*Anser anser*
Lever press	35	*Rattus norvegicus*
Lever press	8	*Mus musculus*
Lever press	5	*Chinchilla laniger*
Feeder entry	12	*Rattus norvegicus*
Licking	9	*Rattus norvegicus*
Move joystick	24	*Macaca mulatta*
Move joystick	9	*Cebus paella*
Move joystick	6	*Papio papio*
Nose poke	8	*Rattus norvegicus*
Nose poke	3	*Mus musculus*
Pecking	76	*Columba livia*
Pecking	8	*Taeniopygia guttata*
Pecking	4	*Aratinga canicularis*
Pecking	3	*Aphelocoma californica*
Perching	11	*Poecile atricapillus*
Perching	6	*Taeniopygia guttata*
Perching	3	*Columba livia*
Perching	3	*Sturnus vulgaris*
Proboscis extension	3	*Apis mellifera*
Room entry	9	*Rattus norvegicus*
Touchscreen	15	*Macaca mulatta*
Touchscreen	5	*Pongo abelii*
Touchscreen	4	*Papio papio*

Review 2: Commercial Equipment

Method

In order to examine if the trends in automated comparative research are related to commercial offerings, we reviewed the online offerings of three major suppliers of commercial behavior research equipment; Lafayette Instrument Neuroscience (Lafayette, IN, lafayetteneuroscience.com), Med Associates Inc. (Fairfax, VT, med-associates.com), and Harvard Apparatus (Holliston, MA, harvardapparatus.com; includes both Coulbourn Instruments and Panlab). As detailed archival records of offerings in the 2000s are not available, this review is not intended to be an inclusive outline of historical changes. Instead, it is intended to be a snapshot of current trends that may relate to recent trends in comparative psychology research. Every item on each vendor's website was manually checked for inclusion by the primary author in October, 2017.

In our analysis, we included any electromechanical devices that could present stimuli or record responses. However, we omitted physiological stimuli and responses (e.g., calorimeters, intracranial stimulation), video and audio measures that required manual analysis, and devices intended for human subjects. For some devices, a single vendor offered multiple variations of a device. To prevent the review from being inflated by near duplicates from the same vendor, we recorded all variations of a device as being the same device. For example, if a vendor offered separate tone generators for 2,800 Hz and 4,500 Hz tones, we simply recorded that vendor as offering a tone generator.

Findings were classified of our review into eight major categories: activity tests, mazes, stimulus devices, response devices, combined stimulus/response devices, reinforcement devices, aversive devices, and rodent-specific tests. Activity tests included activity wheels, automatic doors, feeder head entry sensors, food intake sensors, infrared activity monitors, infrared beams (individual pairs or grid systems), lickometers, place preference apparatuses (without shock), and water intake sensors. Mazes included circular runways, elevated plus mazes, radial arm mazes, T mazes, and Y mazes. Stimulus devices included single, dual, and triple light-emitting diode (LED) stimuli, olfactory systems, tone generators, and white nose generators. Response devices included handhold bars, keys, levers, push/pull knobs, nose poke holes, omnidirectional levers, and response wheels. Combined stimulus/response devices included liquid-crystal displays (LCDs), multicolor and pattern display keys, retractable levers with and without tricolor LEDs, and nose poke holes with one to three LEDs, olfactory inlets, and guillotine doors. Reinforcement devices included grain feeders, liquid dispensers, and pellet dispensers. Aversive devices included shock generators, shuttle boxes (with shock), and shockable running wheels. Rodent specific tests included catalepsy tests, forced swim tests, platform activity monitoring tests, reaching chambers, rota-rod tests, rotameter tests, skilled reach grasp tests, sleep deprivation tests, startle chambers, tail flick analgesia tests, and tail suspension tests. Finally, we noted the intended species for each device. Although some equipment may be adaptable to multiple species, we recorded the species the devices was intended to be used with, as designated by the vendor. For this reason, we also omitted any devices that had no species suggestions.

Results and Discussion

A summary of our findings can be seen in Table 2. We found that rodent equipment accounted for 79.39% of all equipment. Even when not considering the 11.84% of equipment designed for rodent-specific tasks, rodent equipment still accounted for 76.62% of all offered equipment. Pigeon and primate equipment accounted for 8.77% and 7.46% of equipment, respectively. A meager 4.39% of equipment was labeled for other species, including dogs, guinea pigs, and pigs. Although it is likely that some of the equipment offered could be used for species similar to the intended species, the focus of these research equipment companies is clearly on rodent models of behavior.

Table 2

Review of Commercial Research Equipment Offerings

Category	**Rat**	**Mouse**	**Pigeon**	**Primate**	**Other**	**Total**
Activity	20	19	1	1	1	42
Maze	9	8	0	0	0	17
Stimulus	11	11	7	5	4	38
Response	12	10	3	5	1	31
Stimulus/Response	13	13	7	2	2	37
Reinforcement	6	6	2	4	2	20
Aversive	8	8	0	0	0	16
Rodent	11	16	0	0	0	27
Total	90	91	20	17	10	228
Percent	39.47	39.91	8.77	7.46	4.39	100

Only five items matched our general search criteria but did not clearly specify a species, and so were excluded from the review in Table 2. The first item was a response wheel without species designation; other vendors offered a similar product for rats. The other four items were computer vision programs listed without species designations. Computer vision is a relatively new technology, where a computer program analyzes a still image or each frame of a video to determine the location or current behavior of an animal, in real time, or *post hoc*. Two programs we found detected freezing behavior in response to startling or aversive stimuli. One of the freeze-detecting programs was designated as for “rodent species.” The other two programs tracked the movement and location of animals. One was designed to accompany water mazes designed for rats and mice, but the software itself had no species designation. It is likely these computer vision programs are adaptable for similarly sized species, but it is possible that the algorithms are also optimized for rodents or specific procedures.

We also noted some interesting trends in our review. Most problematic for comparative psychology is that no equipment was available for reptiles, amphibians, fish, or invertebrates. It seems unlikely that equipment designed for mammals and birds could be easily used with other taxa. For example, the food and water reinforcement procedures for rats and pigeons may not be effective with reptiles, as temperature change may be much more effective motivator (Garrick, 1979; Kemp, 1969; Krochmal & Bakken, 2003; Krochmal, Bakken, & LaDuc, 2004; Place, Varnon, Craig, & Abramson, 2017). The aquatic environment of fish, and the small size of invertebrates also require special apparatus considerations that would likely make these taxa unsuitable for most commercial equipment. However, it should be noted that custom equipment for fish and invertebrates is possible, and has been created by individual research teams (e.g., fish: Valente, Huang, Portugues, & Engert 2012; invertebrates: Dinges, Varnon, Cota, Slykerman, & Abramson 2017). We also found that all vendors offered red stimulus lights for rodents. This is surprising given that rodents, and most non-primate mammals, do not have red color receptors (Jacobs, 2009). This is an important point considering how vital an understanding of subject species is for comparative research.

In our review, we also observed that prices were generally only available by request. However, most equipment tends to be very expensive. For example, simple operant conditioning equipment may cost between $2,000 to $20,000 (Devarakonda et al., 2015; Hoffman et al., 2007; Pineño, 2014, Varnon & Abramson, 2013).

Although we did not formally record data on human devices, we noted that one vendor offered a wooden pyramid puzzle for $150; we were able to find identical puzzles online for $10 to $20.

Although we cannot suggest a causal effect of equipment offerings on species use in comparative psychology, it is easy to see similarities in limited taxa diversity in both published automated research and available equipment. Comparing the species and automation trends in Figure 2 to the percent of equipment offered by species in Table 2 clearly shows that both are dominated by rodents. Similarly, both the species and response trends in Table 1 and the percent of equipment offered by species in Table 2 also show a strong bias towards rodents, birds, and primates. If trends in species use and automation in comparative psychology are indeed related to commercial research equipment offerings, then perhaps one solution to increase diversity in taxa studied is to explore low-cost automation alternatives created by individual research laboratories. Our third and final review investigates such alternatives.

Review 3: Low-Cost Automation Alternatives

Many researchers have sought custom alternatives to commercial automation to obtain equipment specialized to their research and species, or simply to reduce costs. Behaviorists especially have a long history of creating their own automated equipment (for a review, see Escobar, 2014). One of the most well-known alternatives was the Walter/Palya experiment controller (Palya & Walter, 1993; Walter & Palya, 1984). Although the technology is now somewhat outdated, the Walter/Palya experiment controller was successfully used with a variety of species, including pigeons (Minervini & Branch, 2013), rats (Ranaldi, Ferguson, & Beninger, 1994), bees (Dinges et al., 2013), and rattlesnakes (Place et al., 2017), and is still used by several laboratories today. Such a flexible experiment controller could help increase the number of representative species studied in comparative psychology. In our final review, we examined several journals to see if similar modern alternatives have been developed.

Method

We reviewed the journals *Animal Behaviour*, *Behavior Research Methods*, *International Journal of Comparative Psychology*, *Journal of Comparative Psychology*, *Journal of Neuroscience Methods*, and *Journal of the Experimental Analysis of Behavior*, between the years of 2000 and 2016, for the terms apparatus, automat*[1], experiment controller, microcontroller, and microprocessor. The time period for the review was selected to have the best chance to find articles describing modern technology. We selected articles that contained detailed, replicable, low-cost (i.e., ≤ $1,500 USD sans computer), electromechanical devices that could automatically respond to and/or record behavior. Furthermore, to be included, the description of the device needed to be detailed enough as to permit reproduction in other, unaffiliated laboratories. For the purpose of capturing devices useful for automated comparative research, we excluded devices intended only for human use, devices that only detected virtual behavior of a subject at a personal computer (e.g., mouse clicks), devices that only recorded physiology, and devices that relied exclusively on outdated technology, primarily the parallel port. We also scanned the references of all articles for related works that fit the review's criteria. All articles were manually accessed via institutional databases and publication websites, and then manually checked for inclusion by the primary and second authors. After the primary and secondary authors agreed on article inclusion, a random correspondence check was used ensure accuracy of data.

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[1] The asterisk is interpreted as a wild character by search engines and therefore returns any article with words that begin with "automat," such as "automation" and "automated."

Results and Discussion

Only 11 articles met the criteria to be included in the analysis (see Table 3). It appears that many researchers are using microcontrollers, such as the Arduino family of development boards (Arduino; New York, NY) or the Parallax Propeller microcontroller (Parallax Inc.; Rocklin, CA), to automate experiments. In some cases, the microcontroller itself was solely responsible for automation, and could save data onto an onboard secure digital (SD) card that could be later transferred to a computer, making the system small and portable. In other cases, the microcontroller served as an interface between a laboratory computer and an experimental apparatus. Unfortunately, the species and response trends mirrored those observed in Figure 1 and Table 1. However, some of the devices show promise for truly comparative research.

The earliest device in this review, OpenControl (Aguiar, Mendonça, & Galhardo, 2007) is free computer vision location-tracking and automation software for maze experiments. Although a species is not specifically stated, the article describes typical rodent experiments and provides rodent examples. OpenControl requires a computer with Visual Basic (Microsoft; Redmond, WA) to run the software, which offers a graphical user interface. During an experiment, the software tracks the location of a rodent in real-time, while the computer's parallel port interfaces with devices, such as levers, feeders, and doors. Such devices can be controlled based on the subject's location. Although the paper does not offer specific hardware, it does make suggestions for connecting an OpenControl system to commercial equipment through the parallel port. Unfortunately, parallel ports are somewhat outdated and are no longer standard on most computers. Only users with older computers will likely be able to make full use of OpenControl. However, the computer vision aspects of OpenControl may still be useful on newer computers that lack a parallel port.

Hoffman, Song, and Tuttle's (2007) Electronic Operant Testing Apparatus (ELTOPA), is an operant conditioning apparatus for birds featuring three keys, each with a bicolor LED, and a food delivery system. The ELTOPA is based on the PIC16F877A microcontroller (Microchip Technology; Chandler, AZ) and can transmit data to a personal computer through a serial connection. Although the ELTOPA apparatus is impressive and potentially adaptable, the system appears to be designed specifically for birds and is not a general-purpose system.

Gess, Schneider, Vyas, and Woolley (2011) describe an auditory recognition training system (ARTSy) to train zebra finches in conspecific call-recognition tasks. ARTSy provides food reinforcement when the birds peck a target (detected by an infrared beam) on hearing the appropriate call. The authors suggest that system can be used with any species, but the paper primarily discusses a go-nogo procedure with zebra finches. ARTSy is controlled through a MATLAB (MathWorks; Natick, MA) program on a laboratory computer. Unfortunately, the MATLAB requirement may increase the price substantially for those that do not already have a license.

Varnon and Abramson (2013) describe the Propeller Experiment Controller (PEC), an experiment controller, driven by the Parallax Propeller microcontroller, that is heavily inspired by the Walter/Palya controller (Palya & Walter, 1993; Walter & Palya, 1984). The paper describes how to use the PEC for a teaching laboratory and covers use of over twenty programs in habituation, classical conditioning, and operant conditioning. Programs are suitable for both classroom demonstrations and research. Like the Walter/Palya controller, but unlike most other devices in our review, the PEC is not dedicated to a specific species or set of responses. Instead, the user is free to interface the PEC with a variety of other equipment; the paper also describes how to connect some common equipment, such as levers and stimulus lights. Due to this flexibility, the authors do not provide a specific price but suggest the core components cost less than $100 and describe several inexpensive options. Additionally, PEC is the only system in our review that offers a modular library of code dedicated to behavioral research in addition to programs written for specific experiments. Again, this is much in line with the Walter/Palya controller. The PEC saves data to an onboard SD card and does not require a computer for use, making it the first portable system in our review. Although the primary topic of this paper is devoted to teaching laboratories, other papers describe experimental use with diverse species such as horses (Craig, Varnon, Pollock, & Abramson, 2015), and honey bees (Dinges et al., 2017). Additional information on use of the PEC and other equipment is available on the primary author's website (CAVarnon.com).

Poddar, Kawai, and Ölveczky (2013) describe a home-cage operant apparatus for rats that provides water reinforcement contingent on lever presses or moving a joystick. LEDs are used to signal the start of a trial, while a tone was used to signal availability of reinforcement. The system is designed to control many home-cage apparatuses simultaneously, and entails one or more client computers that control the apparatuses, a trainer computer that controls the client computers, and a master computer that controls the trainer computer over the internet using a graphical user interface. Although the hardware for the individual apparatuses is relatively inexpensive, at about $500, the cost increases substantially when adding the computers, and then averages to around $1400 an apparatus for a 48-apparatus setup.

The ArduiPod (Pineño, 2014) is an operant chamber for rats designed around the Arduino Uno. The ArduiPod requires an iPod Touch or iPhone (Apple Inc.; Cupertino, CA) as a touchscreen and stimulus device. It also features a simple water delivery system for reinforcement. Data can be saved by the iPod or iPhone, making the ArduiPod another portable device untethered to a computer.

Escobar and Pérez-Herrera (2015) released an Arduino-based experiment controller as an update of Escobar's earlier parallel port system (Escobar & Lattal, 2010). The primary offering of the Escobar and Pérez-Herrera (2015) controller is a Visual Basic program enabling a computer to control an Arduino-based apparatus. This system allows a user to run several schedules of reinforcement programs with one or two response devices. Escobar's website (analisisdelaconducta.net) also offers several rodent-related devices and programs. Although Escobar's work appears to be focused on rodents, this system is not a species-specialized apparatus, and could potentially be used with other species, if adequate equipment is designed. However, reliance on a personal computer with the Visual Basic program means that the system is not portable, nor is it currently expandable outside of supported experiment programs. The Escobar and Pérez-Herrera (2015) controller is available for about $200, depending on the equipment selected. The price, however, is only for the core experiment controller; no equipment for an animal is included.

Kuusela and Lämsä (2016) describe a simple artificial flower for use with bumblebees. The flower uses an infrared beam to detect when the bees enter a passageway, and a small drop of nectar can be delivered by a servo-actuated dipper. Each artificial flower costs around $10, with a $100 control unit (driven by an Arduino Mega 2560) able to control up to 32 flowers. The control unit then interfaces with a computer. Although very inexpensive, the dipper feeder does not likely provide the same precision of feeding as other bee equipment that uses syringe pumps to deliver food (e.g., Sokolowski & Abramson, 2010).

Nyguyen, O'Neal, Bolonduro, White, and Kravitz (2016) describe a home cage feeding device for mice that delivers food pellets and tracks when the pellets are removed and consumed. The device is battery-powered and records data onto an onboard SD card making one of the most portable devices in our review. Unfortunately, the abilities of this apparatus are rather limited to recording feeding behavior, and so would likely be best suited as a component of a more involved experiment.

Ponce, Genecin, Perez-Melara, and Livingstone (2016) describe an automated apparatus to train rhesus macaques to participate voluntarily in neuroscience procedures requiring a primate chair. Although the apparatus was designed specifically to train macaques to enter the restraining chair, the automated reinforcement procedures could be used for other research. The apparatus uses a capacitance sensor to detect touch responses, and two ultrasonic sensors to detect proximity. It also can deliver water as a reinforcer and generate audio on a small speaker. The devices in the chair are controlled by an Arduino Uno, and data is transferred to a MATLAB program on a computer.

Most recently, Devarakonda, Nguyen, and Kravitz (2016), developed the Rodent Operant Bucket (ROBucket), an Arduino-based operant chamber for mice literally built inside a small, square bucket. The ROBucket records nose poke activity in three holes using infrared sensors, including a central hole where water can be automatically delivered. It also saves data to an onboard SD card which can be transferred to a computer at a later time, making the ROBucket another portable system.

Overall, many of these low-cost systems are promising, especially when funding is difficult to obtain. Although most are designed for common species and research methods, it is easy to see how they might be adapted to expand research in comparative psychology. Out of the systems we reviewed, it appears that the PEC (Varnon & Abramson, 2013) and the Escobar and Pérez-Herrera (2015) controller show the most promise for comparative work, and are both well-supported by the author's websites. The PEC appears to provide the most species- and method-flexible system, but does require the user to have more technical skills to make use of it, outside of its documented applications. Escobar's controller, and website, appear to provide more traditional rodent equipment using an Arduino / Visual Basic system that may appeal to those with experience with these popular technologies. Any of the systems we reviewed could be useful in removing reliance on commercial equipment and returning control of research to those who conduct it.

In addition to these modern systems, readers may find many other papers and resources that would not fit the strict criteria of our search, but still provide useful descriptions and electronics diagrams of equipment. Some provide rich details sufficient for replication, others provide less details but still offer a good starting point for related projects. Even older papers may offer details that are still relevant to modern electronics and apparatus construction. Some designs include devices to automatically condition the proboscis extension reflex in honey bees (Abramson & Boyd, 2001), pellet dispensers for birds (Berkhoudt, van der Reijden, & Meijmans, 1987), multispecies feeding and watering devices (Crowder, Wilkes, & Huneycutt, 1964), infrared pellet delivery verifiers (Pinkston, Ratzlaff, Madden, & Fowler, 2008), feeding devices for sheep (Sandler, Van Gelder, Karas, & Buck, 1971), devices to record the foraging behavior of flying insects (Sokolowski & Abramson, 2010; Sokolowski, Disma, & Abramson, 2010), universal feeders (Takahashi, 1995), infrared beam response devices for fish (Uter, 1978), lickometers for rodents and insects (Wall, Walters, & England, 1972; Ford, Abramson, Sears, & Gutierrez, 2004), open-source syringe pumps (Wijnen, Hunt, Anzalone, & Pearce, 2014; cavarnon.com/syringepump), and open-source rodent behavior research systems (brodywiki.princeton.edu/bcontrol).

Researchers and students interested in creating their own equipment might also consider hobby electronics and robotics vendors, such as Adafruit Industries (New York City, NY; adafruit.com), Parallax Inc. (Rocklin, CA; parallax.com), Pololu Robotics and Electronics (Las Vegas, NV; pololu.com), Servocity (Winfield, KS; servocity.com), and Sparkfun Electronics (Niwot, CO; sparkfun.com). The websites of these vendors are ripe with easy to use equipment and educational resources. On examining the offerings of hobby vendors, one will quickly see the vast possibilities brought by modern microcontrollers and microprocessors. Microcontrollers are a complete programmable system contained within a single chip, and often designed to interface with other input and output devices, including levers, LEDs, speakers, and feeders. Popular microcontrollers include the Parallax Propeller, and the ARM (ARM Holdings; Cambridge, UK) and PIC microcontroller families; the Arduino is not technically a microcontroller itself, rather it is a development board and software system that makes use of various microcontrollers. A microprocessor is a small, programmable computer processor, which along with other components, can be used to build general purpose or specialized systems. Hobbyist microprocessor platforms include the Beaglebone (Beaglebone.org Foundation; Oakland Twp, MI) and the Raspberry Pi (Raspberry Pi Foundation; Cambridge, UK) microprocessor families. Generally, microcontrollers are better for low-level automation required by experiments, while microprocessors are better for higher-level tasks like user interfaces and displaying video.

Using a microcontroller or microprocessor, it would be easy to create many types of devices. For example, in an operant apparatus, tri-color LEDs can be used as stimulus lights, piezo speakers can be used to play simple audio tones, and micro switches or infrared sensors can act as response devices. Likely the most difficult aspect of an operant chamber is the reinforcement device, however many of the previously mentioned papers provide detailed plans. Much of this custom apparatus work is possible at a very low cost, and only requires rudimentary skills in electronics and programming. Fortunately, the hobby electronics and robotics resources previous described offer more than adequate educational information suitable for a novice. With a moderate time-investment, it would be possible to implement or extend the low-cost automation alternatives described in our review (Table 3) or create new, specialized systems.

Table 3

Low-Cost Automation Devices

Device	**Species**	**Behavior**	**Manipulation**	**Hardware**	**Price**
Aguiar et al. (2007)	Rat	Location	Any	Parallel port	$0
Hoffman et al. (2007)	Bird	3 key pecks	Food delivery, 3 bicolor LEDs	PIC16F877A	$300
Gess et al. (2011)	Zebra finch	Key peck	Food, house lights, calls	Custom circuit board	$1,250
Varnon & Abramson (2013)	Any	Any	Any	Propeller	<$100
Poddar et al. (2013)	Rat	Lever press / joystick	LEDs, tones, water delivery	PC via custom electronics	$1,400
Pineño (2014)	Rat	Touchscreen	Water delivery, video stimuli	Arduino UNO + iOS	$300
Escobar & Pérez- Herrera (2015)	Rat	2 lever presses	Food delivery, house lights	Arduino UNO	$200
Kuusela & Lämsä (2016)	Bumble bee	Flower entry	Nectar delivery	Arduino UNO	$132
Nguyen et al. (2016)	Mouse	Food removal	Food delivery	Arduino Mega 2560	$350
Ponce et al. (2016)	Rhesus macaque	Touch, proximity	Water delivery, audio stimuli	Arduino Pro	$230
Devarakonda et al. (2016)	Mouse	3 nose pokes	Water delivery	Arduino Uno	$150

Another potentially useful technology is computer vision. As with more traditional, electromechanical forms of automation, expensive computer vision tools are purchasable, but some researchers are also creating new open-source solutions (e.g., Aguiar et al., 2007; Conklin, Lee, Schlabach, & Woods, 2015; Kane & Zamani, 2014). For readers interested in developing free computer vision options, we suggest researching the Python programing language (python.org), in conjunction with the scientific analysis package, SciPy (Jones et al., 2001), and computer vision library, OpenCV (Open Source Computer Vision Library, opencv.org).

General Discussion

Our review of trends in species use in comparative psychology shows that, even in recent years, comparative psychology does not take advantage of the vast diversity of potential subject species. This is unfortunate, considering that species-differences are often found when research investigates the behavior of less common subjects. For example, Craig et al. found that honey bees show different trends in responding under fixed-interval schedules of reinforcement than traditional mammalian and avian subjects (Craig, Varnon, Sokolowski, Wells, & Abramson, 2014). Bitterman (1965) also described differences in response patterns in spatial and visual tasks across primates, rats, pigeons, turtles, fish, cockroaches, and earthworms. Interestingly, rats with cortical deconstruction respond more like fish in some visual problems. Finding such species-differences may be important to progressing the field of comparative psychology, especially when they can also be related to physiological processes or evolutionary history.

When considering trends in automated research, use of a limited number of species is further exaggerated. It also appears that the trends in automation may be exacerbated by the limited offerings of commercial research equipment. However, we describe a new movement in affordable automation alternatives that has been created by researchers frustrated with limited or expensive commercial options. We also discuss resources to help interested individuals venture into the world of automation. It is our hope that this information may inspire current and future comparative psychologists to explore new areas in automation with non-traditional subject species.

Although automation techniques are powerful, it should be stressed that direct observation is also an important technique, especially when considering novel species, complex intra-species interactions (e.g., human-dog companionship) and novel research methods. Once direct observation has provided a good understanding of the topography and properties of a behavior, automation techniques may be used to efficiently capture relevant aspects of that behavior. In many cases, the easiest path to collecting data may be to design an experiment around available automation. However, the important characteristics of a behavior may not be those that are captured by the most popular technology. For example, while the count or rate of lever presses are traditional measures in rodent work, response force and duration have been shown to be more important in some rodent psychopharmacology research (Fowler, Filewich, & Leberer 1977; Fowler & Liou, 1994). By initially employing direct observation, it may be possible to design automation around the species and behavioral properties of interest.

In conclusion, we hope that this paper will help renew interest in studying nontraditional species, especially using automated procedures. Our collective efforts to better understand behavior can be enhanced with the addition of automated techniques where applicable, and will likely lead to new avenues for comparative research. We also hope that this paper may help inspire a new generation of comparative psychologists, as the interest of undergraduate students are essential for the future of the field (Abramson, 2015).

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