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Changing Behavior Through Design: A Lab Fume Hood Closure Experiment

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One fume hood in a laboratory can use as much energy as three homes per year. When a fume hood is in use, its door (or "sash") needs to be open, but otherwise it should be closed for safety, as well as to conserve energy. This paper examines strategies to promote fume hood closure behavior. A behavior change experiment conducted in the field tested whether a design signifier (sticker) and comparative feedback extracted from automated building and equipment data would decrease the number of times people left fume hoods open when not in use (while spaces were unoccupied or the hoods were inactive). The experiment included a control building where no fume hood intervention was implemented. The sticker and feedback together resulted in significantly fewer instances of hoods being left open (a 52.8% reduction overall). One year later, with the sticker in place and without further feedback, the instances of hoods being left open when the space was occupied but the hoods were inactive remained significantly lower than baseline. In addition to providing a low-cost strategy to bring about behavior change, findings from this study suggest opportunities to improve fume hood design and to use automated building data to provide laboratory workers with feedback to change their behavior.

Keywords: sustainability, design, environmental psychology, behavior, habits, energy conservation, automated building, safety

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INTRODUCTION

We each go about our daily lives engaging in routine behaviors with little awareness. Most of us consistently close refrigerator, microwave, garage, car, or front doors without consciously making a decision to do so. Such actions are examples of habits. In laboratory settings, there is one door that many people do *not* close consistently: the fume hood sash. Leaving a fume hood open when not actively in use can result in a tremendous amount of wasted energy. The overall aim of the current research is to test whether a simple behavior change intervention can leverage our tendency toward non-conscious action and result in an increase in fume hood closure.

Laboratory Fume Hoods

Laboratory fume hoods are first and foremost safety equipment that protect workers by removing potentially harmful gasses from a building. A fume hood consists of a flat workspace enclosed in a large metal cabinet fronted by a moveable glass door, or sash (see **Figure 1**). A fume hood is equipped with a powerful fan that draws gasses and potentially harmful particulates away from lab technicians as they work, away from the front of the cabinet, and up and out of the building. The

FIGURE 1 | A fume hood.

sash should be closed if no one is actively working at the fume hood. When a fume hood sash is left open, movement in the room (e.g., a person walking by) can alter airflow and cause dangerous fumes to escape from the hood.

Constant air volume (CAV) hoods exhaust the same amount of air continuously, regardless of sash height. Modern fume hoods typically use variable air volume (VAV) fans, which change speed depending on how far the sash is open. The further the sash is open, the harder the fan works to remove air. When the sash is closed, the fan still operates continuously (24/7), but at a lower level, providing some airflow and preventing the buildup of fumes from any chemicals left in the hood.

Because of their role in removing air from a building, laboratory fume hoods can be thought of as part of a building's heating, ventilation, and air conditioning (HVAC) system. HVAC systems in laboratory buildings use 100% outside air to ensure safety (Sahai, n.d.). Even with heat-recovery systems built into many modern HVAC systems, continuously exchanging the air in a building uses a lot of energy. When a VAV fume hood is left open when not in use, it can needlessly increase energy use by increasing the electric load from the fan itself, and also by increasing the number of air exchanges per hour (thereby losing heated or cooled air) above what is required, particularly when a space is unoccupied. Depending on the number and type of hoods present, fume hoods can be a principal factor in a laboratory building energy use (Mathew et al., 2007). Each fume hood is estimated to use the equivalent of three to three-and-a-half times the energy as an average U.S. home (Mills and Sartor, 2005). There are ~500,000 to 1,500,000 fume hoods in the U.S. costing more than $4 billion to operate (Mills and Sartor, 2005).

The overall energy use associated with a VAV fume hood is determined largely by day-to-day habits of a building's occupants (specifically, whether or not the sash is closed when not in use) (Woolliams et al., 2005). Keeping fume hoods closed when not in use can result in substantial energy savings, depending on how a building system is designed, a building's general ventilation requirements, and fume hood design. In addition to impact on energy use, keeping the sash shut when not in use is the safest behavior and best practice for maintaining the integrity of experiments being conducted in a research lab.

Building Occupant Behavior and Energy Use

Fume hood energy use fits into a larger context of buildings and occupant behavior. In the U.S., ~40% of primary energy consumption is associated with buildings (U.S. Energy Information Administration, 2019), which makes buildings a frequent target for energy conservation efforts. At universities and other research institutions, laboratory buildings in particular are a focus of energy conservation efforts because of their high energy use stemming from HVAC requirements and other equipment use (Woolliams et al., 2005; Mathew et al., 2007). Laboratory buildings can consume four to five times more energy than commercial buildings of similar size (Woolliams et al., 2005). However, few studies have examined energy conservation opportunities and interventions in laboratory buildings (Kaplowitz et al., 2012).

A lot of energy conservation efforts focus on technological fixes. The dominant model for whole-building sustainability currently is the LEED program (Leadership in Energy and Environmental Design) (U.S. Green Building Council, 2018). LEED is a building rating and certification system used to guide the construction and renovation of buildings and building systems for energy conservation as well as for water conservation, healthy and sustainable materials, indoor air quality, and more. Typical energy conservation measures might include the installation of high efficiency HVAC equipment and lighting.

Unfortunately, many sophisticated green buildings are falling short on promised energy savings (Newsham et al., 2009; Yudelson and Meyer, 2013). The gap between *expected* and *actual* building performance can occur due to building design and maintenance problems, but gaps can also result from occupant behavior (Brown and Cole, 2009; Li et al., 2014). Building occupants may use equipment in unintended ways, alter equipment, change equipment settings, block equipment, or otherwise act in a manner that increases energy use above what was predicted during the design process. Therefore, building occupant behavior is an important consideration for energy conservation efforts, including fume hood closure (Wesolowski et al., 2010).

Technological and behavior change interventions converge with the use of smart building technologies. Sensors that monitor occupancy and equipment use 24/7 can help pinpoint behaviors that drive excess energy use. In the case of fume hoods, modern labs can be programmed to track instances of sashes being left open when the equipment is not in use. Such technology is particularly helpful when studying or attempting to change behaviors that are frequent and difficult to observe or measure reliably via self-report (Shadish et al., 2002).

Automaticity and Habits

Our cognition and the behaviors stemming from cognition can be organized into two major categories: conscious and non-conscious. Conscious processes are those that we actively control with awareness (Logan and Cowan, 1984). Making plans, weighing options, and making deliberate choices would fall under conscious cognition. Much of our day-to-day lives is governed by non-conscious processes (Bargh and Chartrand, 1999). We continuously think, act, and make decisions with no conscious awareness. Some non-conscious processes are simply instinctual, like the way we reach out and grasp an object. Other non-conscious processes have roots in conscious thought and action and then, through repeated exposures and action over time, become automatic (Bargh and Chartrand, 1999; Bargh and Ferguson, 2000; Graybiel, 2008). For example, learning to ride a bicycle takes conscious effort, but eventually the acts of pedaling, moderating speed, and stopping without falling become automatic.

Non-conscious processes are important for our ability to function day-to-day because they conserve cognitive effort (Kahneman, 2011). If we are able to make decisions, interact socially, and behave automatically in environments and situations with which we are familiar, we are able to save highly valuable energy to deal with new, potentially dangerous environments and situations. Automaticity also allows us to conserve cognitive effort for decisions and behaviors that are consequential and allow other less important ones to become routine. Without non-conscious processes—including habits—it would be difficult for us to navigate our daily lives, where we make countless decisions and carry out numerous repeated behaviors (Neal et al., 2006). Automaticity, then is likely an adaptive function (Bargh and Chartrand, 1999).

Habits are a specially defined type of learned cognition or behavior characterized in part by automaticity. Habits are formed through repeated exposures to and experiences with a specific context or environment. Once formed in a specific environment, habits are then triggered by that environment. Once a habit forms, when a person encounters an environmental trigger, their response is a relatively fixed or rigid (Neal et al., 2006; Graybiel, 2008; Wood and Neal, 2009). For example, buckling a seat belt is an action we have to consciously learn initially, but then it becomes a non-conscious habit over time with repetition in the same environment (i.e., our car). However, if the environment changes—if we climb into the back of a rideshare van with an unfamiliar seat belt configuration—then buckling a seat belt rises to a level of consciousness again.

The connection to the environment, particularly the physical environment, is an important aspect of habits. Cues from our environment can trigger non-unconscious judgments, emotions, and most importantly for the present research, behaviors (Bargh and Chartrand, 1999; Wood and Neal, 2009). As we become more familiar with and knowledgeable about an environment, we are less likely to make conscious evaluations and more likely to act automatically. Neurological activity settles into a pattern (James, 1890; Graybiel, 2008). Those patterns are then activated automatically each time we encounter the context (Ouellette and Wood, 1998; Neal et al., 2006). The combination of repetition, consistent connection to an environment, and our general tendency to conserve cognitive effort for unfamiliar, consequential situations can lead to the formation of habitual behaviors.

Habits are powerful in that they are both difficult to change and can be a stronger determinant of behavior than attitudes or intentions (Ouellette and Wood, 1998; Gregory and Leo, 2003; Neal et al., 2006; Ji and Wood, 2007; Graybiel, 2008; Klöckner, 2013). Relatively little is known about how to successfully initiate habit formation in the real world (Lally et al., 2010). One likely leverage point for habit formation is the context itself (Neal et al., 2006; Verplanken and Wood, 2006; Verplanken et al., 2008). Changing the context, or altering the environment can bring a person's conscious awareness to a situation. An alteration in the environment coupled with conscious awareness has the potential to disrupt a habit and perhaps create an opportunity for a different habit to form.

Because they are driven by non-conscious processes, habits are also difficult to measure. Research has relied on self-report (Verplanken and Orbell, 2003; Verplanken, 2006; Sniehotta and Presseau, 2011). Self-report, by definition, involves conscious thought, so there is a disconnect between the construct (habit) and the measure (the self-report habit index). People may be able to report a routine (a series of connected behaviors that include both conscious and non-conscious thought), but may not be able to report specific habitual, non-conscious aspects of that routine. For example, a person might be able to explain the order in which they complete major tasks in the morning (e.g., shower, comb hair, brush teeth), but would be unlikely to report the specifics of how they carried out those tasks (e.g., which leg stepped into the shower first, what part of their head they combed first, which quadrant of their mouth they brushed first). Thankfully, because of the way human cognition works, we are free of having to make conscious decisions for each little step in a larger routine. But the lack of consciousness for small everyday behaviors also means those behaviors can be difficult to change, particularly without a change in the environment.

Environmental Affordances and Signifiers

When considering cues in an environment, two concepts from environmental psychology are particularly useful. First, environmental *affordances* connect to our perceptual system, our environment, and our actions. Most generally, an affordance is something in the environment—surfaces, layouts, objects, enclosures, and so on—that enables an action or behavior in a particular physical setting (Gibson, 1979). A flat surface affords sitting, a snow-covered hill affords sledding, a cleared path affords walking across terrain. Affordances can be thought of in negative terms as well—a vertical surface does *not* afford sitting, for example.

Objective affordances simply exist in the environment, but humans also alter their environment to create affordances, making an environment more or less suitable for particular actions. Affordances have thus become an important aspect in the design of objects, the built environment, and technology (Norman, 2013). Well-designed objects feature affordances that clearly correspond to the appropriate action, without added information or instruction. For example, a well-designed door would be equipped with a flat panel at the appropriate height on the side that pushes in, and a pull handle on the side that opens out, without the need for signage indicating that one should push or pull the door.

Second, *signifiers* are perceivable cues or signals that provide information or suggest suitable behavior in particular situations or social settings (Norman, 2008). A signifier can be incidental or intentional. For example, a person who arrives to a train platform close to departure time can quickly determine whether the train has already left or has not yet arrived by looking at whether the platform is empty or is busy with people jostling for position. Painted lines on a street signify whether it is appropriate to pass other drivers. A well-worn path connecting two sidewalks suggests where park-goers take shortcuts.

In the case of a laboratory fume hoods, a sliding track and a handle on a sash afford opening and closing. Signage and stickers could serve as intentional signifiers delivering cues for appropriate behavior (closing the hood). On the other hand, a sash left open by a lab-mate could be an unintentional signifier for a different type of acceptable behavior (leaving the hood open). Signifiers could be suggestive of norms, as they can provide evidence of others' behavior.

Feedback and Norms

Providing feedback on energy consumption has proven to be one effective strategy for reducing energy consumption. In a review of more than three dozen energy conservation experiments, households that received feedback on energy consumption reduced energy use 2.5 to 17% (Abrahamse et al., 2005). Providing feedback on energy consumption appears to be more effective at influencing behavior than providing general information on energy conservation and appears to result in more lasting change than using rewards.

Delivering normative messages has also proven to be an effective strategy for increasing pro-environmental behavior, including energy conservation and litter avoidance (Cialdini et al., 1990; Stern, 2000; Allcott, 2011). In a large randomized field experiment, providing comparative feedback that suggested normative energy usage succeeded in reducing household energy use by 2% (Allcott, 2011). In that experiment, researchers used illustrations (smiley faces) to provide customers with feedback on their household energy use relative to that of their neighbors. Similarly, in an experiment with households that received feedback on energy consumption coupled with descriptive normative information (average household consumption in the neighborhood) or injunctive normative information (average household consumption plus an indication of whether the particular household was doing better or worse than average, provided in the form of a happy face or a sad face), providing descriptive normative information resulted in reduced energy consumption for those who were above average consumers, but increased energy consumption for those who were already consuming below average (Schultz et al., 2007). Providing injunctive normative information resulted in reduced energy consumption for those who were above average consumers without the "boomerang effect" for those who were already doing relatively well.

Energy Conservation and Fume Hood Behavior in Laboratories

In a study of laboratories at a large university, Kaplowitz et al. (2012) found generally positive environmental attitudes toward energy conservation among principal investigators, lab staff, and students working in science laboratories. However, as with other areas of environmental behavior (Kollmuss and Agyeman, 2002), Kaplowitz et al. identified an attitude-behavior gap: despite positive attitudes, energy conservation was not a priority in the laboratories and often did not translate into action. Treatment of lab samples, uncompromised operations, convenience, and standardization of lab practices were all reported as being in conflict with energy conservation. In other words, for energy conservation behaviors to occur, they could not be seen as interfering with lab operations in any way. Factors important for choosing new equipment were reliability, quality, and cost (i.e., not energy efficiency). The conservation-related behaviors that study participants did engage in (e.g., equipment sharing, bulk operations, turning off lights) were done primarily for convenience and for monetary savings. While there were significant educational efforts at the university around environmental issues generally, participants noted that they lacked information specific to labs, including energy use and cost. A majority of participants lacked information about the impact of their behaviors (including closing the fume hood sash) on energy use. The biggest barriers had to do with operational constraints, specifically the importance of putting research first, and with safety. "It seems clear that the implementation of energy saving approaches must overcome perceptions that they compromise the ease and productivity of operations in the labs" (p. 587). The authors recommended closing knowledge gaps in part by providing regular feedback to lab users on their behavior and the impact of that behavior on energy use and cost.

A small number of universities have undertaken research on behavioral interventions specifically for fume hood closure. Intervention strategies include awareness-raising campaigns, information provision, the provision of feedback, competition and rewards, and the placement of stickers (Mathew, 2012; University of California Irvine, 2013; Gilly and Michetti, n.d.; Sahai, n.d.). For example, in one laboratory building with 25 labs and 200 fume hoods, approximately half of which were recorded as being left open overnight, researchers undertook an intervention that included a presentation and feedback to principal investigators who oversaw labs in the building (Wesolowski et al., 2010). Feedback was delivered monthly via email. Post-intervention, frequency of fume hood closure increased and average sash height during inactive periods decreased from 9% open to 6% open.

With many behavioral interventions, particularly with awareness-raising campaigns that use competitions and rewards, persistence of effects over time is a challenge. Fume hood behavior is no different (U.S. Department of Energy, 2012). Few laboratory studies have measured effects over time. Feder et al. (2012) implemented a multi-faceted campaign for fume hood closure and measured results immediately and several months later. The intervention consisted of various activities and tools to raise awareness, including a launch party, posters, a website, and stickers. The researchers also held a competition led by "sash patrols" who carried out surprise inspections and awarded stamps to labs where fume hoods were closed when unoccupied. Each stamp increased a lab's chances of winning a prize. Prior to the campaign, only 3.1% of hoods were closed when unoccupied. During the campaign, the figure rose to 61.3%. Eight months after the campaign, the compliance rate dropped significantly (to 14.5%), but not back to pre-campaign levels. The authors concluded that competitions and prizes (and the withdrawal of prizes) might reduce long-term effectiveness.

Two universities tested a large sash-position sticker in the shape of an arrow with a red zone in the upper levels of the sticker and a green zone in the lower levels (U.S. Department of Energy, 2012) (See **Figure 2**). In one case, researchers manually measured sash heights in 10 laboratories before sticker installation and then 2 months later and again several months after installation. In the second case, researchers recorded sash height from an automated building monitoring system in 51 labs during 10-day periods before installation and 1, 2, and 3 months after installation. Both universities found significant improvements in sash closure behavior. The behavior persisted over time, with some isolated exceptions that then became candidates for targeted outreach.

Fume hood interventions have at times created confusion. Stickers placed on fume hood sashes often suggest a safe opening height (when a fume hood is actively in use, the sash should be kept at a height that protects the lab worker's face). The suggested safe level can be mistaken as the appropriate level to keep the sash at *all* times, rather than just when in use (U.S. Department of Energy, 2012). A wide range of acceptable heights can also send confusing messages in terms of normative behavior.

FIGURE 2 | University of California system fume hood sticker.

Gaps in Research

Fume hood closure behavior has substantial implications for energy use. There are several gaps in the existing research, and more research is needed to identify a simple, low-cost, and effective intervention to alter behavior. First, most laboratory behavior interventions have been information-heavy and labor-intensive (i.e., requiring frequent updates, written materials, meetings, etc.). Second, with custom combinations of events, presentations, information campaigns, and emails, existing interventions are difficult to replicate. Third, many studies have relied on manual spot checks for hood closure data, which introduce measurement issues. For example, one study reported that there were instances when lab workers warned each other that a patrol was on the way, which gave them time to close the hood (Feder et al., 2012). Fourth, while automated building data has been used in studies, the data did not account for occupancy. Average sash height, the typical dependent variable derived from building data, might simply reflect changes in activity levels (e.g., labs have become more or less busy), rather than instances when hoods are left open when no one is working. Finally, there have been no fume hood behavior change intervention experiments that included a control group.

Current Research and Hypotheses

Lab fume hood closure behavior corresponds well with the concept of habit. Closure is a simple behavior with no sub-steps, no need for significant learning to occur, no other behavior that needs to be undone or stopped, and the existing fume hood closure behaviors (or lack thereof) are not particularly strong (Verplanken and Wood, 2006). In addition, the context is stable and it is easy to tie the behavior to an environmental cue or signifier. Over time, closure behavior ideally should require no conscious cognitive effort on the part of lab workers, and no sustained effort on the part of lab or building managers to support the ongoing behavior. In the short term, establishing closure behavior as a non-conscious habit might require briefly raising awareness. Feedback, particularly feedback that suggests norms, is an effective behavior change strategy (Schultz, 2014), and also might be useful in bringing attention to the behavior. The following study was designed to test whether a simple, low-cost intervention will increase fume hood closure behavior. Specifically, the intervention includes a closure signifier (sticker) and comparative feedback.

Hypothesis 1: Installation of the sticker will be associated with a decrease in the number of times fume hoods are left open when the area is *occupied*.

Hypothesis 2: The addition of feedback will further decrease the number of times fume hoods are left open when the fume hood area is *occupied*.

Hypothesis 3: Installation of the sticker will be associated with a decrease in the number of times fume hoods are left open when the area is *unoccupied* and the hood is likely inactive.

Hypothesis 4: The addition of feedback will further decrease the number of times fume hoods are left open when the fume hood area is *unoccupied* and the hood is likely inactive.

Hypothesis 5: Over the long term, the presence of the sticker will continue to be associated with a reduced number of times the fume hood is left open when the area is *occupied*.

Hypothesis 6: Over the long term, the presence of the sticker will continue to be associated with a reduced number of times the fume hood is left open when the area is *unoccupied*.

MATERIALS AND METHODS

Setting

The study took place on the campus of a large research university where the heating and cooling load from laboratory buildings accounts for 50% of energy use. The university has undertaken an extensive laboratory ventilation management program that balances safety and sustainability, taking into account both the amount of air exchanged to protect workers from potentially hazardous materials and the energy required to provide that air. Across campus, standard laboratory ventilation requirements (air changes per hour) have been reduced where possible. To conserve energy and to encourage safe laboratory practices, staff from the university's facilities, environmental health and safety (EH&S), and sustainability offices identified fume hood closure behavior as a top priority to further conserve energy and to protect workers.

Based on the type of equipment in use, the type of laboratory activities housed in buildings, and overall similarity among all laboratory buildings on campus, university environmental health and safety staff and building managers advised researchers on the selection of two buildings for the study. The two interdisciplinary science buildings chosen for the study house a mix of molecular biology, biomedical engineering, genetics, biotechnology, and nutrition labs using similar types of substances in experiments.

The experimental building has ∼250,000 square feet. Four floors of the building house 45 fume hoods. Nine hoods were removed from the study because they were vacant or hibernated, and one was removed because it was kept open 24/7 to provide extra ventilation in a room with an abundance of heat-producing equipment ($n = 35$). The control building has ∼175,000 square feet with 84 fume hoods on five floors. Three hoods were removed from the study because they were vacant ($n = 81$). All of the fume hoods in both buildings are VAV, similar in design, and have vertical sashes.

Students, faculty, and staff who may be exposed to chemicals while working are required to complete the university's Laboratory Safety program, which consists of about 2 h of lecture and video instruction[1]. The training addresses fume hood safety, specifically the importance of closing the hoods to avoid air contamination and reduce the risk of fire[2]. People dealing with radioactive, potentially infectious, or other specific hazardous materials are required to complete additional training. Individual labs may, at their discretion, offer lab-specific training and/or address lab procedures during lab meetings. The amount and content of individual lab discussions varies widely, depending on the principal investigator and, if applicable, lab manager.

Research Design

The study used a quasi-experimental design with a no-treatment control group and pre- and post-test. The intervention occurred from late March to early May. It included collecting baseline data, followed by data from a time period with stickers installed, and then a time period with feedback (in addition to the stickers, which remained in place) (see **Table 1**).

Fume hood data accumulated 24/7 for nearly 8 weeks. Data collected during Spring Break (which occurred in April) and on weekends were excluded from analysis. Data were equalized for day of the week and number of hours across time periods to create

TABLE 1 | Experimental design.

Building	Two-week measurement period			
	Period 1 baseline	**Period 2 sticker**	**Period 3 sticker+feedback**	**Period 4 follow-up**
Experimental	O*	X_1 (Sticker) O	X_2 (Sticker + Feedback) O	X_1 (Sticker) O
Control	O	O	O	O

O indicates measurement; X indicates intervention.

[1]Prior to the study, the lead author completed the university's laboratory safety training. When walking through labs, the researcher wore safety glasses and followed other guidelines regarding dress and procedures.

[2]In 2008, a UCLA researcher died as the result of burns suffered after chemicals ignited during an experiment in a fume hood. The case is used in laboratory safety training to stress the importance of safe lab practices.

the most accurate comparisons. Each time period in the analyses consisted of 2 weeks[3].

Baseline data were also compared to follow-up data collected for 2 weeks, 1 year later (in April 2018). One year was chosen because it was considered substantial enough to test whether the intervention had lasting effects, and because activity levels would be expected to be similar at the same time of year as when the original experiment took place.

Intervention

The intervention in the experimental building consisted first of a sticker placed on fume hoods (see **Figure 3**). The sticker took the form of a smiley face, cut in half, with one half installed on the frame and one half installed on the glass of the sash. Closing the sash results in a complete smiley face, while leaving the sash open leaves the sticker "broken."

Two weeks after the stickers were installed, feedback based on unoccupied closure data was posted throughout the experimental building. Feedback included an image for each fume hood in the building—a smiley face for fume hoods that were rarely left open unoccupied, a straight face for fume hoods sometimes left open unoccupied, and a surprised face for often open when unoccupied (see **Figure 4**). Feedback sheets also included a note stating "Good lab practices go hand in hand with good research," a note that one fume hood can use as much energy as three homes in a year, a statement emphasizing that fume hoods should be closed every time they are not actively in use, and a footnote regarding the source of the data (from the automated building system). One week after posting, the feedback was updated. One week later (at the end of intervention), the feedback was removed. No further feedback was posted, though the stickers remained.

Dependent Variables

The dependent variables for the study were (1) the number of times a hood was left open when occupied and (2) the number of times a hood was left open when unoccupied during a 2-week time period (as shown in **Table 1**). Each building has an Energy Management Control System (EMCS) that continuously collects data points on equipment use, occupancy, and more. To capture dependent variable data during the study, a university programmer created an EMCS report based on room occupancy and fume hood closure. More specifically, the two dependent variables, which were also referred to as "alarm states" in the EMCS reports, were defined as follows:

- *Occupied alarm:* While an area was occupied and the fume hood sash was left open $>3''$ for more than 2 h[4,5].
- *Unoccupied alarm:* While the area was unoccupied for 15 or more minutes and the fume hood sash was left open $> 3''$.

Each EMCS logged hood closure and occupancy status for every 15-min increment, 24 h per day. Researchers downloaded data from each EMCS and then calculated alarm state frequencies (times a hood was left open) for each hood.

FIGURE 3 | Fume hood sticker.

Analytical Strategy

Data were analyzed using generalized estimating equation (GEE) models in SPSS for Mac (version 24). The models included data for each hood from each of the two buildings from all time periods (Period 1/Baseline, Period 2/Sticker, Period 3/Sticker+Feedback, Period 4/Follow-up). Data from one time period for a particular hood cannot be considered independent from data from a subsequent time period for that same hood. For example, in the experimental building, data from the Period 1 for a given hood is not independent from data from Period 2 for that same hood. GEE accounts for lack of independence among data points.

The dependent variable (the number of times a hood was left open in a given time period) ranged from zero to 84 and contained considerable variance relative to the mean. The model was specified with negative binomial distribution with log link, which is appropriate for models with count data with a lot of variability. The model was also specified with AR (autoregressive order) 1 working correlation matrix, which is applicable in situations with repeated measures over evenly spaced time intervals. Pairwise comparisons were used to test each hypothesis (i.e., to test for differences between each time period for each building).

RESULTS

Occupied Trends

During the Period 1/Baseline Period, hoods in the control building were left open while occupied an average of 9 times. Hoods in the experimental building were left open while occupied an average of 12.5 times (see **Table 2**).

[3]Models that included weekend days resulted in the same outcome. The weekday model enabled the data to be matched on day of the week and for equivalent total hours to be calculated cleanly, with a buffer around spring break.

[4]For fume hood closure, three inches was used as an approximation to allow for small structural issues (e.g., if a sash was slightly off level with the hood frame and unable to close completely) and hoods where the number and size of hoses and power cords running under the sash made it impractical to achieve 100 percent closure.

[5]Two hours is the default alarm criteria that has been used by building managers since the building management systems were installed to alert them of open hoods in *occupied* spaces without generating false alarms. The timeframe was chosen because it suggested lab workers were engaged in bench or computer work nearby, rather than actively engaged with the fume hood.

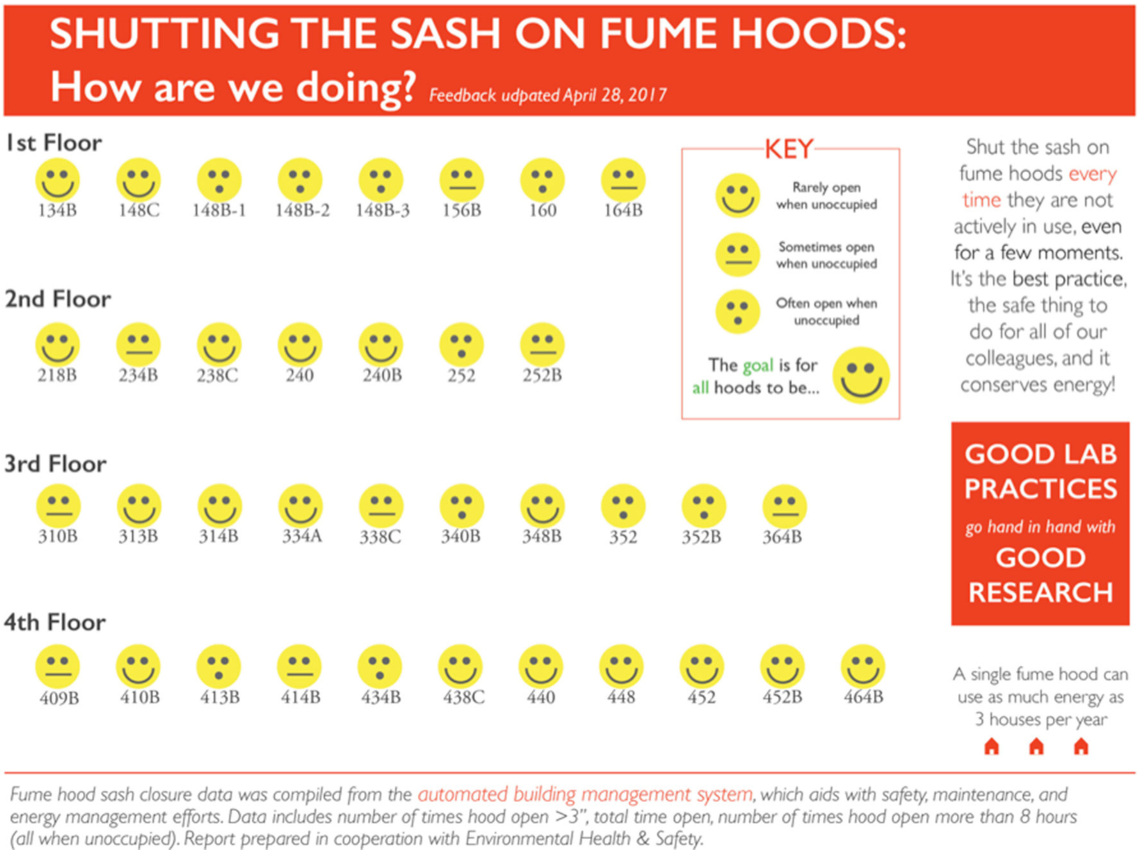

FIGURE 4 | Sample fume hood closure feedback report.

During Period 2/Sticker Period, the mean number of times hoods were left open in the control building dropped from 9 to 8.2 and in the experimental building dropped from 12.5 to 9.3. During the subsequent period when feedback was added (Period 3/Sticker+Feedback Period), the number of times hoods were left open in the control building rose to 11.3, while in the experimental building dropped to 5.9.

Unoccupied Trends

During the Period 1/Baseline Period, hoods in the control building were left open while unoccupied an average of 10 times. Hoods in the experimental building were left open while occupied an average of 22.1 times (see **Table 2**). The control building mean was significantly lower than the experiment building mean at baseline.

During Period 2/Sticker Period, the mean number of times hoods were left open in the control building dropped to 9.7 and in the experimental building dropped to 17.9. During the subsequent period when feedback was added (Period 3/Sticker+Feedback Period), the number of times hoods were left open in the control building rose to 12.4, while in the experimental building dropped to 12.7 (see **Table 2**).

Experimental Effects

Overall, the intervention had a significant effect on closure in both occupied (Wald Chi-Square $= 15.066$, $p = 0.001$) and unoccupied (Wald Chi-Square $= 18.229$ $p < 0.001$) states (see **Table 3**).

Occupied Times

Figure 5 shows specific pairwise comparisons for *occupied* time periods. Hypothesis 1 posited that installation of the sticker would be associated with a decrease in the number of times the fume hoods were left open when an area was occupied. There was no main effect of the sticker on closure activity (Period 1/Baseline Period compared to Period 2/Sticker Period in experimental building, mean difference $= -3.2$, $p = 0.178$).

Hypothesis 2 posited that the addition of feedback would further decrease the number of times the fume hoods were left open when an area was occupied. The model showed a significant effect with the addition of feedback (Period 2/Sticker Period compared to Period 3/Sticker+Feedback period in experimental building, mean difference $= -3.5$, $p = 0.05$ and Period 1/Baseline Period compared to Period 3/Sticker+Feedback period in experimental building, mean difference $= -6.6$, $p = 0.012$).

In the control building, there was no significant change from Period 1/Baseline Period to Period 2, when the sticker

TABLE 2 | Mean number of times hoods left open.

Occupancy	Time period	Building	Mean	Std Error	95% confidence interval	
					Lower	Upper
Occupied	Period 1/Baseline	Control	9.0	1.7	6.28	12.90
		Experiment	12.5	2.9	7.96	19.68
	Period 2/Sticker	Control	8.2	1.4	5.87	11.55
		Experiment	9.3	2.1	6.07	14.39
	Period 3/Sticker + Feedback	Control	11.3	1.6	8.46	14.99
		Experiment	5.9	1.3	3.83	9.04
Unoccupied	Period 1/Baseline	Control	10.0	2.0	6.70	14.93
		Experiment	22.1	4.2	15.17	32.06
	Period 2/Sticker	Control	9.7	1.8	6.80	13.91
		Experiment	17.9	4.0	11.59	27.70
	Period 3/Sticker + Feedback	Control	12.4	2.0	9.11	16.93

TABLE 3 | Overall model effects.

	Source	Wald CHI-square	DF	SIG (p)
Occupied	(Intercept)	339.505	1	0.000
	Time period	4.253	2	0.119
	Building	0.072	1	0.788
	Time period * building	15.066	2	0.001
Unoccupied	(Intercept)	415.037	1	0.000
	Time period	2.448	2	0.294
	Building	3.455	1	0.063
	Time period * building	18.229	2	0.000

was in place in the experimental building (mean difference = 0.8, p = 0.462). The number of times fume hoods were left open in Periods 2 and 3 (when the sticker and then sticker+feedback interventions were in place in the experimental building) *increased* significantly (mean difference = 2.3, p = 0.039; mean difference = 3.0, p = 0.004).

Unoccupied Times

Figure 5 also shows specific pairwise comparisons for *unoccupied* time periods. Hypothesis 3 posited that installation of the sticker would be associated with a decrease in the number of times the fume hoods were left open when an area was unoccupied. There was no main effect of the sticker on closure activity (Period 1/Baseline Period compared to Period 2/Sticker Period in experimental building, mean difference = −4.1, p = 0.224).

Hypothesis 4 posited that the addition of feedback would further decrease the number of times the fume hoods were left open when an area was occupied. The model showed a significant effect with the addition of feedback (Period 2/Sticker Period compared to Period 3/Sticker+Feedback Period in experimental building, mean difference = −5.2, p = 0.014 and Period 1/Baseline Period compared to Period 3/Sticker+Feedback Period in experimental building, mean difference = −9.3, p = 0.004).

In the control building, there was no significant change from the Baseline Period to the Sticker Period (mean difference = 0.3, p = 0.814). The number of times fume hoods were left open in the Sticker and Sticker+Feedback Periods *increased* (mean difference = 2.4, p = 0.052; mean difference = 2.7, p = 0.033).

Long-Term Effects

Occupied Trends

During the 2-week follow-up period 1 year after the original experiment, hoods in the control building were left open while occupied an average of 9.9 times, similar to Period 1/Baseline Period (9.0). Hoods in the experimental building, where the sticker was still in place, were left open while occupied an average of 7.5 times, an increase from the Period 3/Sticker+Feedback period (5.9), but lower than both the Period 2/Sticker (9.3) and Period 1/Baseline (12.5) periods (see **Table 4**).

Unoccupied Trends

During the follow-up period 1 year after the intervention, hoods in the control building were left open while unoccupied an average of 10 times, the same as Period 1/Baseline. Hoods in the experimental building were left open while unoccupied an average of 17.1 times, an increase from the Period 3/Sticker + Feedback period (12.7), slightly lower than the Period 2/Sticker period (17.9), and lower than the Baseline period (22.1) (see **Table 4**).

Experimental Effects

Occupied

Hypothesis 5 posited that over the long term, the presence of the sticker would continue to be associated with a reduced number of times the fume hood is left open when the area is *occupied*. In the experimental building, there was a main effect of the sticker on closure activity, comparing the occupied Baseline Period to data 1 year later (mean difference = −5.0, p = 0.008).

Unoccupied

Hypothesis 6 posited that over long term, the presence of the sticker will continue to be associated with a reduced number of

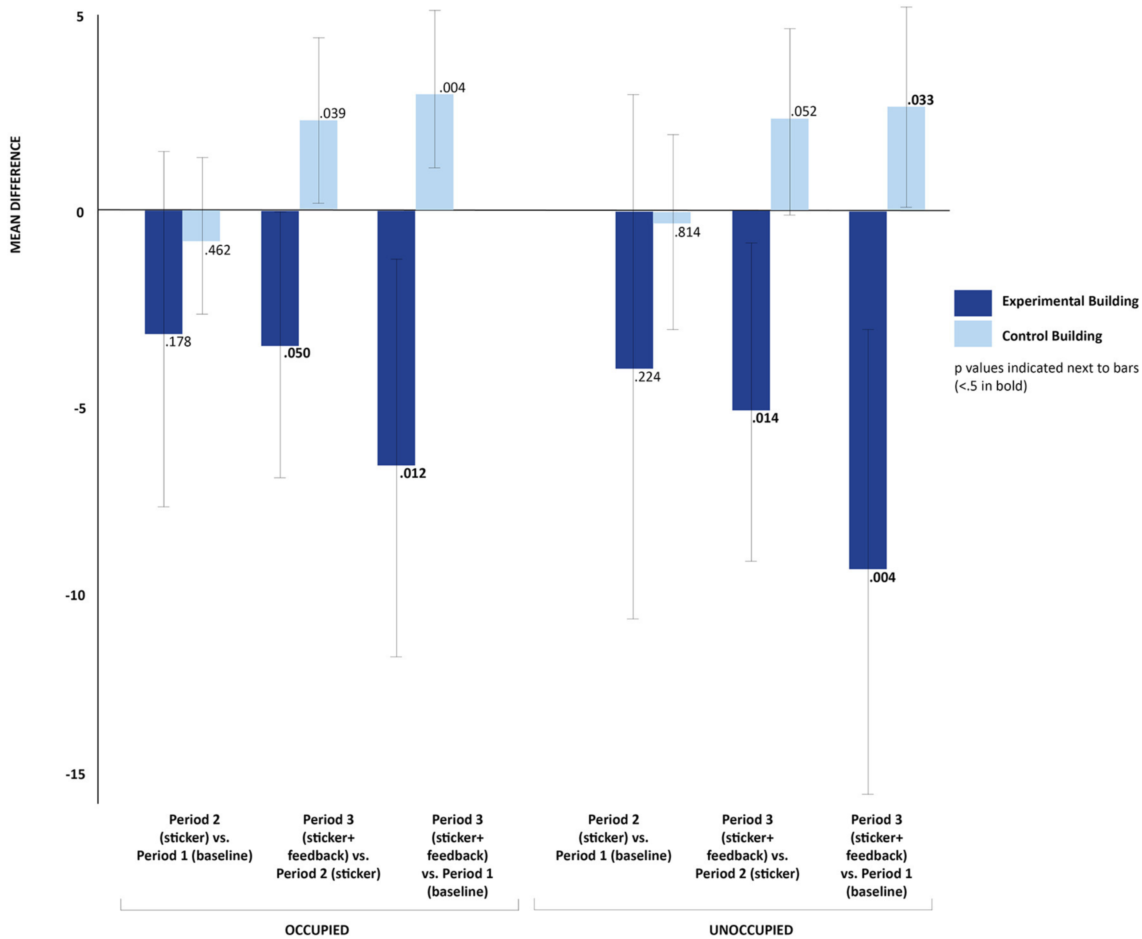

FIGURE 5 | Pairwise comparisons, mean number of times hoods left open.

TABLE 4 | Mean number of times hoods left open long-term.

Building status	Time period	Building	Mean	Std. Error	95% confidence interval	
					Lower	Upper
Occupied	One year later	Control	9.9	1.5	7.31	13.36
		Experiment	7.5	2.5	3.94	14.24
Unoccupied	One year later	Control	10.0	1.8	7.03	14.33
		Experiment	17.1	4.2	10.56	27.56

times the fume hood is left open when the area is *unoccupied*. In the experimental building, there was no main effect of the sticker on closure activity, comparing the unoccupied Baseline Period to data 1 year later (mean difference $= -5.0$, $p = 0.168$).

DISCUSSION

The aim of the current study was to test whether a simple intervention could increase fume hood closure behavior. The study was designed to leverage a human tendency toward non-conscious action, using a permanent signifier to prompt a repeated behavior. The study also employed comparative feedback. Other than feedback posted shortly after stickers were installed, there was no communication to raise awareness regarding the fume hoods or energy conservation more generally.

Overall, the intervention had a significant effect on closure behavior. In the occupied state, mean number of times hoods were left open dropped 25.6% in the experimental building during the sticker period, and 52.8% overall (from baseline through sticker plus feedback). In the control building, mean number of times hoods were left open dropped 8.9% during the initial period after baseline, and rose 25.6% overall. One year later, the mean number of times the hoods were left opened in the experimental builidng remained significantly lower than baseline.

In the unoccupied state, mean number of times hoods were left open dropped 19% in the experimental building during the sticker period, and 42.5% overall. In the control building, mean number of times hoods were left open dropped 3% during the sticker period, and rose 24% overall. One year later, the mean number of times hoods were left open in the experimental building was ∼20% lower than baseline, which was statistically similar to the start of the intervention.

Results supported three of the six hypotheses. During the intervention periods, results did not support hypotheses stating that the installation of the sticker alone would result in a decrease in the number of times fume hoods were left open (when occupied or unoccupied), but did support hypotheses stating the addition of feedback would result in a decrease in the number of times fume hoods were left open. One year later, results suggest that the sticker alone was enough to continue to reduce the number of times fume hoods were left open, but only in the occupied state.

Although the mean number of times hoods were left open in the experimental building decreased after installation of the sticker, the change was not significant. It is possible that the sticker alone was not enough to elicit behavior change. Another possibility is that the sticker's effectiveness was delayed, or took longer than the 2-week measurement period.

Habit formation does take time. Researchers from one study concluded that adopting a new eating, drinking, or physical activity habit can take anywhere from 18 to 254 days (Lally et al., 2010), not the 30 day window often promoted in popular culture. Acquiring automaticity for behaviors likely depends on the complexity of the behavior (i.e., the more complex the behavior, consisting of more steps, with a higher likelihood that some of those steps involve more conscious decision making and action, the longer it takes). Given the simplicity of the target behavior here, which consisted of only one step (the simplest behavior in the Lally et al. study, drinking a water at lunch each day, consisted of at least two steps), it would be reasonable to expect a relatively quick change. Still, the timeframe for behavior change may have been longer than the sticker-only period. It is also possible that it took time for workers to notice the sticker if they were not actively working at a fume hood in the first days of the study.

From the results, it can only be concluded that the sticker in combination with the feedback had an effect. There is evidence that feedback and social norms are effective in the context of energy conservation (see Schultz, 2014). It is also possible that the feedback simply served to bring attention to the sticker's function. A simple solution, like the sticker, might not work without something additional to bring it into conscious awareness initially or to suggest the importance of forming a new behavior.

Comparisons between baseline and activity 1 year after installation of the sticker show that when a fume hood area is occupied (presumably when the sticker is visible while workers are busy working at something other than the fume hood), the sticker continues to have an effect. However, when a fume hood area is unoccupied, there appears to be no significant effect. The results suggest that the intervention did not result in habit formation. When visible, it seems as though the sticker is an effective reminder to close the hood. But without an additional input to bring the closure problem to people's attention (such as feedback), the sticker does not appear to be enough to increase closure behavior. The sticker might prove more effective in a lab with an open layout design where fume hoods are very visible.

Straight comparison of results with similar studies is difficult, as this experiment used count data (emphasizing each act of closure) and accounted for occupancy. Results are consistent with a sash patrol campaign (Feder et al., 2012), which achieved an unoccupied closure rate of 61.3%, a large improvement over the 3.1% closure rate prior to the experiment. However, several months after the campaign, the closure rate reverted to pre-intervention levels. Most other studies used average sash height opening during a study period.

Energy savings were not calculated for this study, but depend on how a building and its equipment are designed. Others implementing an intervention similar to the one presented here may expect to see a decrease in the number of times people leave fume hoods open, but the amount of energy savings that fume hood behavior change translates into will be dependent on specific circumstances in a building, including how a building and its equipment are designed. Wesolowski et al. (2010) found that actual energy savings were less than expected because the fume hoods in the study were equipped with combination sashes (horizontal and vertical sashes). In that study, fume hoods with vertical sashes – like those in this study—realized the most energy savings. Building managers primarily interested in energy savings should consider the relevance of fume hood closure behavior for their building and fume hood design. Newer technologies include audible alarms and sashes that close automatically with inactivity, but are more complex and require expertise to install or can require significant investment for retrofit or replacement (Sartor and Kasliwal, 2007; Becerra et al., 2018). Given the simplicity and low cost of this intervention (negligible cost of printing stickers, plus labor to place them on hoods and to compile and post initial feedback), the payback period for the intervention should be quite short even with modest savings. In addition, as noted above, fume hood closure is critical for safety and research integrity.

This study contributes to the literature in several ways. Importantly, this is the only fume hood behavior change experiment incorporating a control building (specifically, using objective, automated building data in both an experimental and a control building). In addition, while other studies have used automated building data to track sash opening size, opening size simply may be a function of the level of work activity at a hood. The key behavior of interest is having people *close their fume hood each time they cease actively working at the hood*. This study is the first to account for activity by using occupancy data in conjunction with sash height and use instances of closure as the dependent variable. Moreover, the study introduced an intervention that costs little and requires very little labor over the long term. Most prior hood-closure interventions combine several components that require frequent communications, including events and meetings.

Limitations

Although the experimental and control buildings were matched as closely as possible in terms of the type of work being performed in them, the groups were non-equivalent. It is possible that work activities in two buildings varied at the time of the study, influencing amount of fume hood use, and posing a threat to internal validity. However, there were no informational campaigns or known events taking place at the time of the study that would provide an alternative explanation for the observed effects.

Given that the experimental group began with a higher rate of leaving the fume hoods open, statistical regression to the mean could be a threat to internal validity. However, in the case of occupied times, by the end of the experiment, the average number of times fume hoods were left open was higher in the control building than the experimental building (i.e., the two did more than converge). It would be very unusual for an experimental group to regress toward the mean so much that it would fall below the initially lower control group, so regression to the mean is an unlikely alternative explanation for the results. In the case of unoccupied times, by the end of the experiment, the average number of times fume hoods were left open in the control building had increased and experimental building had decreased such that they almost, but did not quite converge. It is more difficult to rule out regression to the mean in this case, but it is still an unlikely explanation, as the groups were not purposefully assigned to conditions based on pre-experiment data (the buildings were assigned to experiment or control conditions before baseline data was compiled). Overall, the patterns observed in the data during the course of the experiment suggest it is unlikely that regression to the mean was a driving factor behind the findings.

The study is limited because it used a sample on one university campus, which limits its generalizability.

Future Research and Design

This study could be repeated in other settings, ideally with a larger number of fume hoods and more equal experimental and control groups. The ability to remove the sticker to isolate its effectiveness without initial feedback, or to randomly assign the order of feedback and sticker, as well as a longer experimentation time would also be useful in future studies.

An intervention that more closely approximates a physical design change, experimentation with different hood closure designs, or a comparative study of existing hood closure designs would be a useful extension of this study. The prevailing thought in laboratory energy conservation and fume hood management has been that, "hood installations require a strong sash management plan that includes periodic training and awareness, informational placards, and possibly penalties and rewards for proper use" (Mathew et al., 2007). However, there is an important connection between the design of the hood and lab workers' behavior and the potential for a design change to lessen the need for a labor-intensive management plan for existing hoods has not been thoroughly explored. This study can also inform the design of new hoods to take occupant behavior into account.

Finally, automated building management systems open new opportunities to provide building occupants with feedback and potentially effect change. Extracting data from a system that was not designed with behavior in mind is difficult. With some foresight, automated building management systems can be programmed to make it easy to extract data that can be used to provide feedback or to track behaviors, ultimately to reduce energy consumption in buildings.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Cornell University Institutional Review Board. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

KA conceived of the study, designed the study and the intervention materials, oversaw data extraction, conducted the data analysis, and wrote the paper. NW assisted in study design, oversaw study implementation, and edited and contributed to the final manuscript.

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