The Effect of Real-Time Feedback on Indoor Environmental Quality

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Abstract. Due to improved insulation, decreasing indoor environmental quality (IEQ) is an emerging issue in the design of sustainable and energy-efficient buildings. Poor IEQ has severe long-term implications for the occupants' health. Manual airing is a promising energy-efficient solution to combine good insulation and healthy IEQ. However, occupants' behavior is crucial for its effectiveness. Digital nudging can help to influence people's behavior, e.g., by means of giving feedback. We conduct a field experiment over four weeks, in which we provide real-time IEQ feedback to nudge occupants towards opening the windows. We find a significant improvement in IEQ for offices in the treatment group, but also see that the nudge's effectiveness reduces over time, possibly as a result of habituation. This experiment paves the way for further studies examining the design of nudges towards improving IEQ.

Keywords: Digital Nudging, Indoor Environmental Quality, Health & Well-being

1 Introduction

Globally reducing greenhouse gas emissions (GHG) is one of the greatest challenges of our time. The building sector accounts for 30% of the total energy consumption worldwide [1] and increasing the energy efficiency of buildings is a promising lever to achieve reduction of GHG emissions. A common measure to raise the energy efficiency of buildings is the improvement of the building's insulation [2], [3]. However, high insulation is also linked to a decrease of buildings' indoor environmental quality (IEQ) [4]. Poor IEQ can cause detrimental effects on human health, well-being, and productivity [5], [6] and is associated with a broad range of negative long-term effects such as severe respiratory diseases or decreased decision-making performance [6], [7].

A widespread countermeasure against poor IEQ in well-insulated buildings is the implementation of heating, ventilation and air conditioning (HVAC) technology [8], [9], but energy consumption is a grave drawback of HVAC [8], [10]. Alternatively, natural ventilation, e.g., by manual airing, is promoted as an energy efficient solution to maintain the positive effect on air quality and health [10], [11]. However, occupants

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often struggle to strike the right balance of ventilation, e.g., because they do not sense the gradual deterioration of environmental quality. Therefore, Schibuola et al. [11] recently called for the use of real-time feedback on the IEQ to trigger the occupants' manual airing, but do not yet provide empirical evidence. Feedback is one means of (digital) nudging, which aims to influence human behavior unobtrusively [12]. However, nudges need to be planned carefully as they must catch the user's attention to work properly [13]. Against this background, we aim to contribute to a better understanding of the applicability of digital devices to nudge incidental activities – such as opening the windows – in an environment that requires strong focus on the primary tasks – such as work. In this context, it is unclear if a nudge can catch the occupants' attention and motivate them to suspend work in order to ventilate. Therefore, we elaborate on the following research question: *Can real-time feedback on indoor environmental quality effectively nudge office occupants in a computer-dominated work environment towards natural ventilation in order to improve the indoor environmental quality?*

We employ a field experiment with a total of 32 occupants in 15 shared offices of a German research institute to investigate the effectiveness of nudging natural ventilation. This is done by means of a prototypical, sensor-based display screen providing visual and quantitative feedback on the office's current IEQ. Our digital nudge aims to make the occupants aware of poor IEQ and, thereby, implicitly influence behavior, but does not directly hint at opening the windows. In our evaluation, we find differences in IEQ when comparing the treatment group before the nudge and with the nudge as well as when comparing the treatment group with a control group, which did not get any feedback. The results indicate that the nudge induces a behavior change towards opening the windows regularly when the IEQ drops. While this effect is strong in the first days of the experiment, it decreases over time and converges to an IEQ higher than the baseline without nudge. A survey with 17 of the 32 participants further substantiates the effectiveness of the nudge based on the participants' self-perception.

The remainder of this paper is structured as follows. Section 2 aims to establish a common understanding on the assessment of indoor environmental quality and the concept of (digital) nudging. The research design and methodology are presented in Section 3. Section 4 describes the study's results. The theoretical and practical implications of our research are discussed in section 5. The work concludes with a critical view on the study and an outlook on future research.

2 Related Work

Indoor Environmental Quality

A multitude of studies show that the quality of the air we breathe can have significant impact on our health [14]. The same holds true for other environmental factors such as thermal comfort and noise [15]. Other studies find that humans spend a large majority of their time indoors: A large-scale study funded by the US government found that the percentage of time Americans spent inside buildings is as high as 87% [16]. These two streams combined are the motivation for research in the context of indoor environmental quality, which aims to establish an indoor environment worth living. This topic gained importance with improved insulation in energy-efficient buildings accounting for a reduced air exchange and, thus, limiting IEQ [4].

Poor IEQ is linked with severe health issues and impaired well-being [5], [17]. Besides negative short-term effects like the *Sick Building Syndrome*, literature lists a broad range of detrimental long-term consequences of bad indoor environments, including respiratory diseases and decreased performance in decision-making [6], [7], [18]. IEQ has also been shown to have a major impact on the occupants' productivity in office environments [6], [9]. While these effects primarily impact the individual that is exposed to poor IEQ, healthcare costs and loss of working hours may also adversely affect economy and society.

IEQ includes various aspects that influence life inside buildings. However, the particular aspects differ depending on the use case. In its most narrow form, it is similar to the concept of indoor air quality, commonly referred to as IAQ, but can also include hygiene, noise, vibration, among other factors [19]. In our study, we apply the Indoor Environmental Index (IEI), an index proposed by Moschandreas and Sofuoglu [20]. It describes IEQ primarily based on air quality and thermal comfort and consists of two sub-indices, the Indoor Air Pollution Index (IAPI) and the Indoor Air Discomfort Index (IDI). IDI valuates the thermal comfort (or discomfort) experienced due to the temperature and relative humidity in the room. IAPI additionally assesses the amount of organic gases (formaldehyde and total volatile organic compounds (TVOC)), inorganic gases (carbon monoxide and carbon dioxide (CO_2)), total particulate matter (PM10 and PM2.5), and biological particulate matter (bacteria and fungi) in the air. Both values are combined to an index ranging from 0 to 10, where 0 denotes very good environmental quality and 10 represents very poor environmental quality.

Several solutions have been proposed in literature to improve IEQ. In highly insulated buildings, HVAC technology is often applied to ensure regular air circulation. However, HVACs have a vast negative impact on the building's energy consumption [8], [10]. Several studies, therefore, investigated the potential of natural ventilation and window airing and found that short-term window airing can significantly improve IEQ [21]. Therefore, we aim to investigate the potential of digital nudges to help people acquire a desirable ventilation behavior.

(Digital) Nudging

People often have several options for action in different situations in their lives. To make a decision, the processing of information is required. Thereby, heuristics are often applied to facilitate and accelerate the decision-making process by reducing the amount of processed information [22]. However, heuristics can lead to biases, i.e., systematic errors, like misjudging probabilities [23]. This builds the theoretical foundation for nudging, which is a concept based on insights from behavioral economics and has been proposed by Thaler and Sunstein about a decade ago [24]. It aims to change environments and situations in such a way to increase the probability of certain behaviors. Thus, these changes could ultimately lead to a different decision.

Nudging can be applied in various settings and involve different techniques. Nudges, which are single instantiations of nudging, are designed in such a way that neither financial incentives are set nor something is prohibited or directly recommended to influence people's behavior. Table 1 provides an exemplary list of nudges that are widely used in literature. One type of nudge is the incentive. It is described by Hansen and Jespersen [25] as making the consequences of a choice visible, because visible information can be processed more easily. The salience nudge uses this by taking advantage of a cognitive bias that predisposes individuals to focus on items that are more prominent or emotionally striking [26]. A typical nudge used in many application domains is setting defaults. It uses individuals' tendency to stick to the status quo and takes advantage of their resistance to change [27]. Another technique to nudge an individual is providing feedback [12] with the goal to evoke a certain behavior or change of behavior. Social norms, on the other hand, are rules of society that differ from culture to culture and make up what is seen as normal, acceptable, and respectful behavior [28]. Using this can influence individuals showing the same behavior as the social group [29]. Croson and Shang [30] showed that people tend to adapt the amount they donate, when they are presented with social norms. When they are told that most people donate less than them, they also donate less, and vice versa. While this list of nudges is not exhaustive, it helps to demonstrate, how nudging can influence an individual's subconscious and therefore, decision making.

Table 1. Exemplary nudges and studies showing their effectiveness

Nudge	Description	Study showing effectiveness
Incentive	Showing consequences of the decisions made [25] – not to be confused with financial incentives, which are not considered as nudge. An example would be the display of costs for an ongoing call. It does not change the charging model but might lead to shorter calls.	[31]
Salience	Designing important information in such a way that they are more visible [32]	[33]
Default Setting	Using default settings to remain with the status quo [29]. An example would be the current discussion about changing the default of organ donor from opt-in to opt-out.	[34]
Giving feedback	Providing users with feedback when they are doing well or making mistakes [12]. An example would be an electronic road sign that reacts to the vehicle's speed with a smiling or sad face	[35], [36]
Social Norms	Providing information about rules, standards and, appropriate behavior within a group of people [37]	[38]

Transferring the concept of nudging into the context of information systems enables further possibilities to nudge individuals to a certain behavior. Weinmann et al. [12] describe digital nudging as guiding individuals' behavior by means of digital user interfaces and several studies have yet examined the effectiveness of digital nudging.

Enabled by the ubiquity of sensor technology, feedback has become a common way of nudging, e.g. in the context of energy efficiency [36], [39–41]. Tiefenbeck et al. evaluate the effect of real-time feedback on energy use during showering [36]. Wargocki and Da Silva demonstrate the effectiveness of CO_2 feedback in school environments to improve classroom air quality [39]. Jensen et al. investigate the social effects of CO_2 feedback devices in residential buildings [40]. While these studies address related questions, to the best of our knowledge research yet fails to evaluate the effectiveness of real-time IEQ feedback to change ventilation behavior in a work environment, in which people focus on their primary tasks. Our work approaches this question and aims to give first indication of the effectiveness of nudging in this context.

3 Research Design

This work aims at better understanding the effect of real-time IEQ feedback, as a means of digital nudging, on human ventilation behavior in a work environment. We collect empirical evidence, analyze ventilation behavior under the influence of nudging, and evaluate user acceptance of the nudge in a field experiment. The following sections describe the experimental setup of the field experiment and the collected measures.

The field experiment

In the field experiment, we collect empirical evidence for the feasibility of digital nudging in a German university-based research institute. Since most work is performed via the computer, activities are predominantly sedentary. The experiment includes 15 offices equal in size and layout and reaches 32 constant office occupants, of which 23 are male and nine female. All participants are in the age range of 25 to 40 years. We refrained from including additional offices, although it would have increased the sample size, since their layout differed substantially from the selected offices and would introduce additional confounding factors affecting the statistical analysis. Initial office selection further catered for planned absence to ensure continuous office presence throughout the field experiment. Thus, the chosen sample size allows for maximum comparability among offices. Before starting the experiment, offices were randomly assigned to either the control group (seven offices) or the treatment group (eight).

The study took place over four weeks in the cold season in February and March 2019. During that time, both groups were equipped with a data logger measuring the office's IEQ. To build a baseline for comparison, there is no nudge for neither the treatment nor the control group in the first two weeks of the experiment, but the sensors already collect IEQ data. In the second phase, the nudge phase, offices in the treatment group are additionally equipped with a display that provides real-time IEQ feedback, while the experimental setting remains unchanged for the control group. Both the data logger and the display were only installed with the occupants' prior consent. Participants were unaware of the exact goal of our research but were informed that the study aims to assess the building's environmental quality. They were further unaware whether their office is in the control or the treatment group until the beginning of the nudge phase. Figure 1 illustrates the experimental setup.

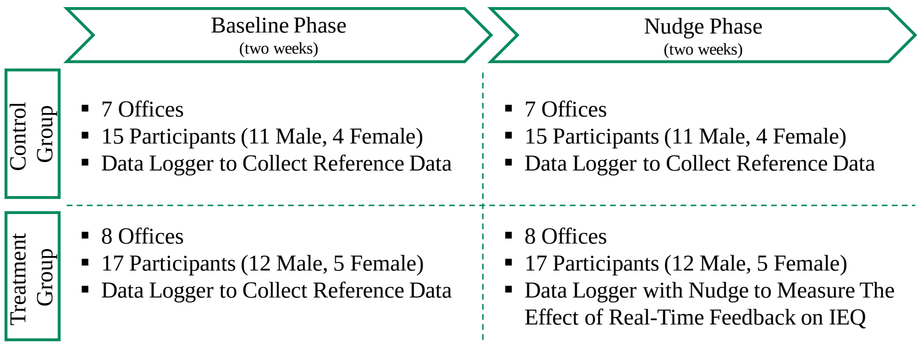

Figure 1. Experimental setup

The setup of the field experiment enables us to compare the ventilation behavior between the treatment and the control group, but also within the treatment group before and with the nudge. Based on the experiment design, we claim that the nudge is the most plausible explanation for differences in behavior between the groups and phases.

Measures

In order to analyze the participants' ventilation behavior, various measures are collected throughout the experiment. This includes environment data from the data loggers, based on which an Indoor Environment Index (IEI) is derived for the nudge. Finally, we conduct a survey to capture participants' self-perception and user acceptance. The following sections describe the data logger, the nudge and the survey in more detail.

The data logger

At the beginning of the field experiment, we installed data loggers measuring IEQ parameters in all participating offices. The data logger collects data on the office's temperature (in °C), relative humidity (in %) as well as the carbon dioxide (CO_2, in ppm, that is, parts per million) and total volatile organic compounds (TVOC, in ppb, that is, parts per billion) concentrations. The data loggers are prototypically built with Arduino microcontrollers, Raspberry Pi single-board computers, and sensor modules. Figure 2 displays the technical infrastructure.

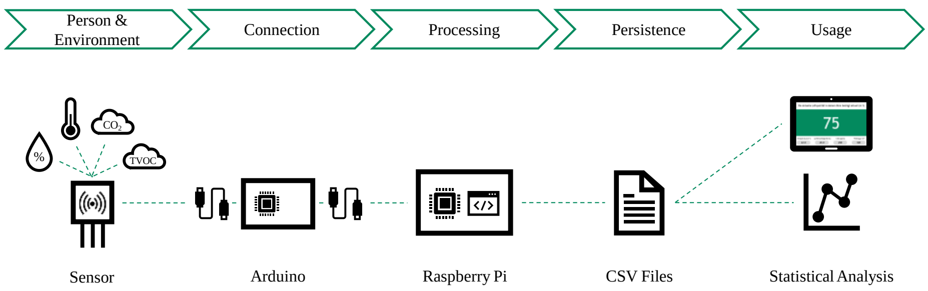

Figure 2. Data logger prototype aligned with the JDCF data flow by [42]

Technically, it uses the Java Data Collecting Framework (JDCF) from Beckmann et al. [42] to collect and process data. Following their suggestion, we describe the data flow along the dimensions *Person & Environment*, *Connection*, *Processing*, *Usage*, and *Persistence*. For the *Person & Environment* step, a combined sensor for humidity, temperature, CO_2 and TVOC collects environmental parameters of the office. To establish the *Connection*, an Arduino probes the sensor in an interval of five seconds and reads sensor data via an I²C bus using a C program. Raw data then is passed via USB to a Raspberry Pi, which utilizes an implementation of the JDCF to realize the *Processing* part. Finally, the data logger uses comma separated value files as the *Persistence* form to prepare data for further *Usage* within a statistical analysis.

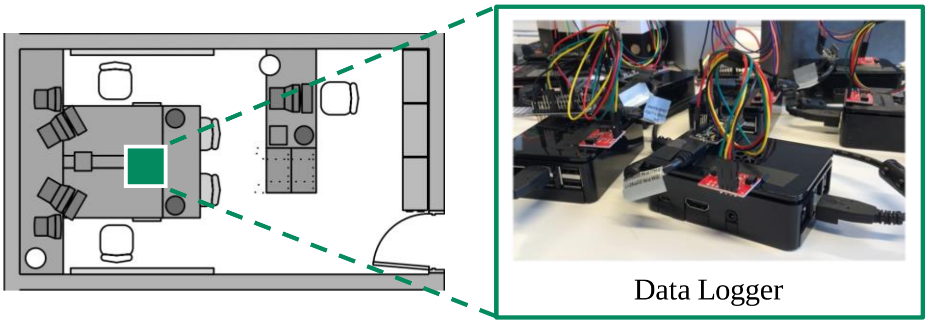

Figure 3. Typical structure of an office and placement of the data logger

We place the loggers on top of the desk approximately in the middle of each office and at least 50 centimeters away from all large technical devices (Figure 3), in order to obtain comparable and reliable sensor data. Staff is instructed not to move the data loggers. To prevent problems resulting from the use of low-cost sensor technology, all sensors are calibrated against a high-quality sensor before the start of the experiment.

The nudge

In order to nudge the participants towards natural ventilation in case of poor IEQ, we base on the concept of visualizing feedback. Therefore, after two weeks of data collection without feedback, we attach the Raspberry Pi of the treatment group to the backside of a seven-inch display and use a 3D-printed bracket to ensure an upright placement of the display. Based on sensor data from the data logger, this display allows us to provide feedback on the current IEQ of the office. To do so, we aim to design and develop an interface that catches the user's attention and nudges them towards opening the windows without explicitly requesting it. Therefore, we divide the screen into a main part that shows an aggregated value for the IEQ and a bottom part that additionally displays the raw sensor values of the temperature, relative humidity, CO_2, and TVOC sensors. The screen refreshes in intervals of five seconds.

To make IEQ more tangible in the main part of the display, we use an adapted version of the Indoor Environmental Index (IEI) proposed by [20]. This adapted IEI (aIEI) differs from the original form in two ways: First, we omit several pollutants such as bacteria or fungi, which are included in the original form, but quite expensive to measure. Second, for presentation purposes, we transform the original scale (0 to 10, where 0 denotes the best environmental quality) to the more intuitive 100-to-0 scale, where 100 is the best value. The calculation of the aIEI builds on data from the last fifteen seconds to avoid erratic changes and increase robustness.

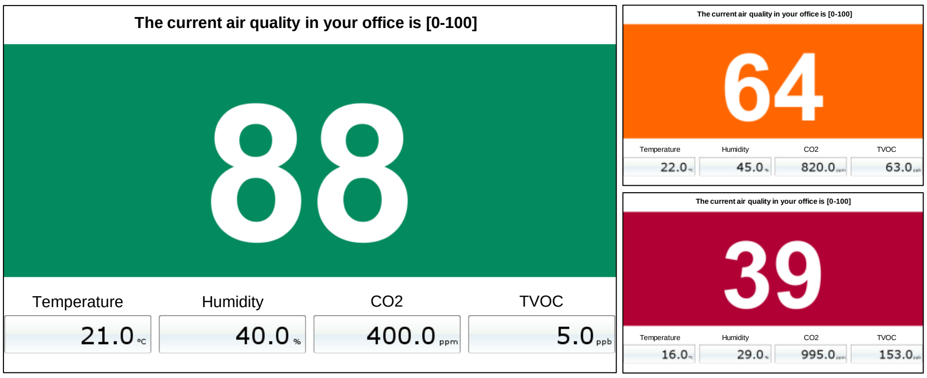

Figure 4. User interface of the display

The nudge uses different background colors (Figure 4) for the display's main part to emphasize the numerical aIEI value. Following related work on emotional feedback [40], [43], colors range from green to red. The background is green at values 65 or above, orange with an average environmental quality below 65 but at or above 40, and red when the aIEI drops below 40. While these limits are based on the data collected within the baseline phase, they align with descriptive IEI statistics [20].

The survey

In order to further support our findings, we conduct a survey after the experiment. The survey comprises overall 20 items with a five-level Likert scale as well as free text fields. Besides collecting data on office presence and occupancy, items are inspired by the technology acceptance model [44]. Therefore, items are grouped in personal preferences and attitude, perceived usefulness of the provided feedback, and the perceived ease of use of the provided display, including the frequency of use. In accordance with our research question, we further asked if the participants perceived the displayed feedback as distracting and if the continuous use of the feedback is imaginable. Items on personal preferences and attitude were e.g., "Good air quality is important for me" and "I perceive the indoor air quality in my office as good". Items on the perceived usefulness of the provided feedback were e.g. "My ventilation behavior has changed due to the provided feedback", "I perceive the feedback as distracting", and "The air quality has improved due to the feedback". Finally, we include free text fields for participants to provide both positive and negative feedback.

4 Results

The experiment yields a dataset that comprises the levels of CO_2, TVOC, relative humidity, and temperature in 5-second intervals for 15 offices over four weeks in February and March 2019. This section outlines the findings obtained from analyzing this dataset. Our analysis is inspired by similar research on digital nudging [35], [36].

We performed several steps of data preprocessing to prepare raw data for data analysis. First, to account for small time offsets and maintain comparability among different offices, we split data into 15-second intervals and averaged the values within that interval. Second, we removed the weekends to exclude days with very low presence of occupants. Third, we calculate the aIEI for each time interval and office based on this dataset. The resulting dataset consists of N = 1,728,000 IEQ observations with a mean aIEI of 47.91, a median of 48.24 and a standard deviation of 15.42. Thereafter, we separated the dataset into treatment and control group and pooled it according to the two experiment phases (baseline and nudge). We then derive the daily mean aIEI per office for each group and phase. Table 2 summarizes the resulting descriptive statistics.

Table 2. Descriptive statistics of control and treatment groups' aIEI

Group	Phase	Min	5th %ile	Median	Mean	95th %ile	Max
Control	Baseline	31.60	35.88	50.93	**50.77**	63.85	72.40
	Nudge	26.94	30.02	50.79	**50.10**	67.05	73.92
Treat-ment	Baseline	21.33	27.68	46.34	**45.71**	57.91	63.06
	Nudge	22.60	29.12	48.44	**49.83**	72.05	81.41

The results indicate that the control group's ventilation behavior did not change throughout the experiment, since both median and mean during the nudge phase are on a similar level during the baseline phase. In contrast, a clear upward shift of all analyzed values can be observed for the treatment group, although their aIEI in average is below the level of the control group. Comparing the mean aIEI from the control group to the treatment group's IEQ mean during the baseline phase, the control group had an 11.07% higher IEQ compared to the treatment group. However, during the nudge phase, the control group's IEQ was only 0.54% better. The initial discrepancy in the baseline phase may be a result of the small sample size and individual differences in both groups.

The highest gain can be observed in the 95th percentile and maximum values with an increase by 24.42% (72.05, compared to 57.91 without feedback) and 29.10% (81.41, compared to 63.06 without feedback). This indicates that nudging successfully raised awareness for IEQ. Consequently, more offices reached a high aIEI on a daily basis, which is a promising sign for our experiment. However, the marginal change in the lower range of aIEI values also reveals that some offices did not change their behavior due to the nudge. The boxplots in Figure 5 illustrate the differences between the groups in each phase based on daily averages.

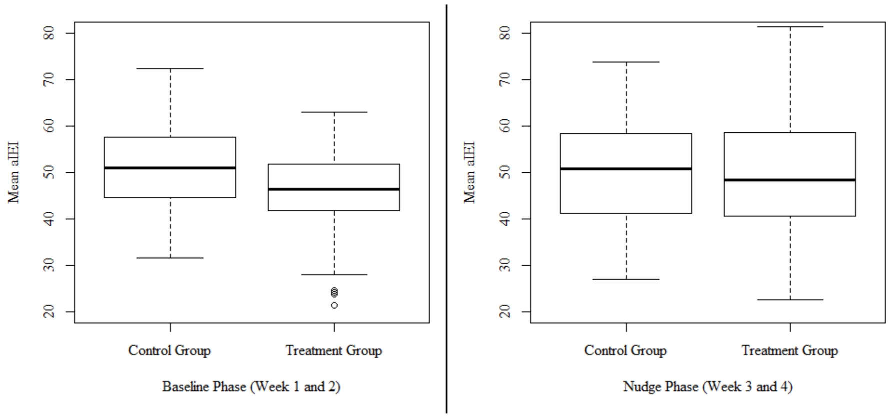

Figure 5. Mean aIEI of baseline and nudge phase

We aim to analyze the significance of the shift in the aIEI mean between the experiment phases. To do so, a paired two-sample *t*-test is a common approach, e.g. in [35]. For a *t*-test to be applicable, the mean of the two samples should follow a normal distribution. Hence, we test each dataset for normality using the Shapiro-Wilk-Test. Table 3 summarizes the results. Since $p > .05$ for all data sets, the normality assumption holds.

Table 3. Shapiro-Wilk-Test for normality - overview of the derived *p*-values

Group	Control Group		Treatment Group	
Study Phase	Baseline	Nudge	Baseline	Nudge
***p*-value**	.9371	.1885	.2236	.5299

To account for possible autocorrelation within the time series, we apply the Ljung-Box test, which again yields $p > .05$ for all datasets. Thus, we have no autocorrelation and can perform a paired sample *t*-test to test the significance of differences in mean between the two experiment phases. The results are summarized in Table 4.

Table 4. Paired sample *t*-test of pooled IEQ data for baseline and nudge phase

Perspective	Control Group	Treatment Group	Baseline Phase	Nudge Phase
Comparison	Baseline vs Nudge	Baseline vs Nudge	Treatment vs Control	Treatment vs Control
$N_{treatment}$	70	80	80	80
$N_{control}$	70	80	70	70
***p*-value**	.684	.014*	< .001***	.897
***t*-statistics**	0.41	-2.53	3.56	-0.13
df	69	79	146.58	147.76

For the control group, we expect to see no change in ventilation behavior and aIEI across both phases, as no feedback on the IEQ was provided. We can confirm this expectation statistically, since the change in the control group's aIEI across the experiment duration is not significant with $p_{control} = .684$, $t(69) = 0.41$. In contrast, the treatment group significantly improved their aIEI with $p_{treatment} = .014^*$, $t(79) = -2.53$ in the nudge phase when compared to the baseline phase. Thus, we can assume that the nudge in average did have a measurable impact on the targeted ventilation behavior.

The survey results of 17 of the 32 occupants substantiate our statistical findings regarding the nudge's effectiveness. Eleven participants from the treatment group and six from the control group took part in the survey. According to the survey, only six of all 17 survey participants (35.29%) consider the indoor air quality in their office to be good, although 16 participants (94.12%, n=17) agree that good indoor air quality is generally important to them. Furthermore, ten of the 11 survey participants of the treatment group (90.91%) confirmed that they used the display to evaluate their IEQ on a frequent level. The same amount of participants in the treatment group states to have changed their natural ventilation behavior due to the provided feedback, which is in line with our statistical findings. Furthermore, only two participants in the treatment group perceived the feedback as distracting, whereas seven participants (63.64%, n=11) state that they did not feel distracted. Overall, three fourths (75.00%, n=16) of all survey participants would like to (continue to) use such a device to monitor their IEQ.

However, a closer look at the treatment group in the nudge phase qualifies the findings about the nudge's effectiveness in part. For the purpose of this analysis, we visualize the average aIEI during the nudge phase for the treatment group (Figure 6) in 15-seconds intervals. In this course, we identify a downward trend in the treatment group's mean aIEI over the two weeks of nudging. This trend indicates that the nudge has a significant effect in the beginning of the experiment, but its effectiveness reduces over time. At the end of week 4, it finally converges to a level, which is higher than the treatment group's mean aIEI in the baseline phase. This is in line with other nudging experiments and is commonly explained with a habituation effect towards the nudge [35], [36].

To overcome habituation effects, we recommend to regularly adapt the nudge to preserve its positive effects on the ventilation behavior. This can, for example, be accomplished by personalizing the nudging limits and set individual goals regarding the ventilation behavior.

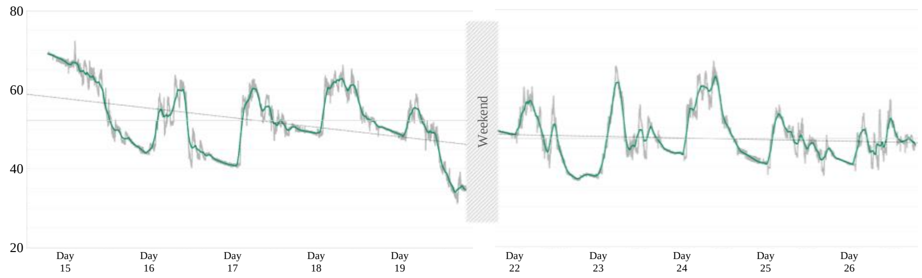

Figure 6. Average aIEI development in the nudge phase – treatment group

Another evidence for the high relevance of inter-personal differences emerges when looking at the individual IEQ charts of single offices. As assumed from the descriptive statistics, some offices did not change their behavior. This might explain the marginal change in the lower IEQ segment. While we do not exactly know, why the nudge did not work for them, we assume that a low interest in IEQ, resistance to change their habits, work stress not leaving time for incidental activities, or specific personality traits are possible influencing factors. One participant confirmed in the free text field of the survey that work stress has an influence on their perception of IEQ and stated to have covered the display, because the changing IEQ values distracted them from their work.

5 Discussion

The study presented in this work has several theoretical and practical implications. Our research contributes to theory by laying important groundwork for a better understanding of how to design nudges. Specifically, we find that people might get used to the nudge and argue that the design of interventions should account for this habituation effect by incorporation longitudinal evaluation of the nudge's effectiveness.

From a practical point of view, it presents empirical evidence that real-time feedback based on low-cost technology is an effective means to positively influence ventilation behavior and, thus, help improve the IEQ in a working environment, where ventilation is a secondary task. This bases on the finding that the treatment group's IEQ on average significantly improved in the nudge phase compared to the baseline phase in a paired sample *t*-test, while there is no significant difference for the control group. A survey further substantiates this claim and indicates increased awareness among the test office occupants for air quality and its related health issues as a result of the nudge. It also shows that some participants are enthusiastic about establishing real-time IEQ feedback over the long term to foster an air-quality- and health-conscious working environment.

6 Conclusion

In this study, we conducted a field experiment to test if real-time IEQ feedback can effectively nudge occupants towards opening the windows in an office environment, where most work is performed at the computer and ventilation is a secondary task. We investigated sensor data from 15 shared offices with 32 participants collected over four weeks. During the last two weeks, the nudge phase, occupants of offices in the treatment group received real-time feedback on the office's IEQ via a display in the office. The control group did not receive any feedback during the time of the experiment.

Although we conducted this field experiment with the necessary care, limitations restrict the informative value of our results. First of all, we find that the nudge's effectiveness reduces over time. While the average IEQ in the treatment group strongly increases in the first days of the nudge phase, the same cannot be found at later days. Possibly as a result of habituation to the nudge, the IEQ level in the treatment group finally converges to a level, which is higher than in the first two weeks of the experiment. Second, although the treatment group's IEQ in average improves with the nudge, we see high variations in the offices' individual IEQ profiles. In some offices of the treatment group, we can observe no or only little difference between the phases with and without nudge. This might be explained by people's different personality traits or attitudes towards IEQ and their own health, but also as a consequence of work stress that does not leave time for incidental activities such as opening the windows. Third, we aimed to control as many external factors as possible that may have an impact on the result while not interfering with the participants' daily work and habits. Nevertheless, factors exist that were not controlled during our study due to restrictions regarding the interference with the daily work routine (e.g., requiring a certain behavior) or sample size (e.g., the position of the office inside the building).

Future research should address these issues by gathering more data in general as well as in multiple cases differing in their geographic location to verify external validity. Further studies should also build on our work by evaluating the effectiveness and longevity of IEQ nudges. This could be achieved by comparing different designs of nudges, e.g., by adding elements of gamification and competition to increase motivation. Finally, a closer look into inter-personal differences of the nudge's effectiveness is yet missing and might build the foundation for the design and development of personalized nudges.

In general, the findings of our study lay important groundwork to better understand how to guide people towards changing their ventilation behavior. In times, in which an increasing number of buildings is highly insulated, maintaining a good IEQ is important to preserve the occupants' health. According to research, manual airing still is the best method to achieve a good indoor climate, while saving our planet.

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