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Environmental Significance Statement

In a room containing objects, the surface area that is relevant for interactions with indoor air is larger than that of the walls, floor, and ceiling alone. Objects such as furniture, window coverings, books, and clothing contribute to surface area while subtracting from the volume of air in the room. On average, the contents of bedrooms, kitchens, and offices increase their surface area by 50% and decrease their volume by 10% compared to an empty room. The results of this study can be used to improve understanding of the behavior of gases and particles in indoor environments.

Total Surface Area in Indoor Environments

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Abstract

Certain processes in indoor air, such as deposition, partitioning, and heterogeneous reactions, involve interactions with surfaces. To accurately describe the surface-area-to-volume ratio in a room, we have characterized the surface area, volume, shape, and material of objects in 10 bedrooms, nine kitchens, and three offices. The resolution of the measurements was ~1 cm. The ratio of surface area with contents to that without contents did not vary by type of room and averaged 1.5 ± 0.3 (mean ± standard deviation) across all rooms. The ratio of the volume minus contents to nominal volume averaged 0.9 ± 0.1 and was lower for kitchens compared to bedrooms and offices. Ignoring contents, the surface-area-to-volume ratio was 1.8 ± 0.3 m^{-1}; accounting for contents, the ratio was 3.2 ± 1.2 m^{-1}, or 78% higher. These two ratios did not vary by type of room and were similar to those measured for 33 rooms in another study. Due to substantial differences in the design and contents of kitchens, their ratios had the highest variability among the three room types. The most common shape of surfaces was flat rectangular, while each room also had many irregularly-shaped objects. Paint-covered surfaces and stained wood were the two most common materials in each room, accounting for an average of 42% and 22% of total surface area, respectively, although the distribution of materials varied by room type. These findings have important implications for understanding the chemistry of indoor environments, as the available surface area for deposition and reactions is higher and more complex than assumed in simple models.

Key Words: surface, area, volume, built environment, indoor air, deposition

Introduction

Since humans spend about 87% of their time indoors, on average,[1] understanding indoor air quality is essential for characterizing the relationship between health and the environment. Conceptual and numerical models are important tools for understanding the transport, transformation, and fate of gases and particles indoors. Among the inputs to such models are the surface area and volume of the indoor setting, often combined as the surface-area-to-volume ratio or the surface-to-volume ratio, yet researchers often assume that the surface area and volume of a room are determined by the dimensions of its walls, floor, and ceiling while ignoring the contribution of any contents of the room. There have been some exceptions that considered real-world rooms and accounted for at least the major furnishings.[2-4]

For processes such as deposition, resuspension, partitioning, and heterogeneous reactions, surface area plays a critical role. Deposition of gases and particles onto surfaces removes them from the air, thus eliminating inhalation exposure to them. However, deposition on surfaces can cause detrimental effects both directly, such as deterioration of materials[5] and damage to electrical equipment[6] by particles, and indirectly, such as ozone-induced secondary emissions of aldehydes from indoor surfaces.[7] Resuspension is an important source of particles indoors, and it depends on surface characteristics, including geometry.[8, 9] Semi-volatile compounds partition between the gas phase and the liquid phase, in which they are usually adsorbed on surfaces.[10, 11] In addition, surfaces can be a source of emissions of gases and particles. Heterogeneous reactions, such as between nitrous acid and nicotine to form carcinogenic nitrosamines,[12] take place at the gas-surface interface. At a gross level, these processes do not discriminate between the surface area of walls and that of objects in the room.

One example of the importance of surface area indoors is its appearance in mass-balance equations that are widely used to model concentrations of gases or particles in a room. As shown in Equation (1), a typical model accounts for advective transport into and out of the room, emissions, loss by reaction, and loss by deposition, where C is the concentration of the contaminant inside the room, V is the volume of the room, Q is the volume flow rate of air into and out of the room, C_{out} is the concentration immediately outside the room, E is the emission rate, k is the first-order reaction rate coefficient, v_d is the deposition velocity, and S is the surface area of the room.

$$\frac{d(CV)}{dt} = QC_{out} - QC + E - kCV - v_d SC \tag{1}$$

This equation is a simplification that assumes deposition to be consistent across all materials and orientations. In reality, deposition velocities may vary by surface material for reactive gases, and only upward-facing surfaces participate in deposition of particles due to gravitational settling, in which case the last term in the equation should be a summation over each material and orientation, each with its own v_d and S. Dividing the simplified equation by V produces the surface-to-volume ratio (S/V), which is often employed in indoor air quality models, in the last term. In theory, S should be the total surface area accessible to the contaminant, and V should be the volume of air in the room.

The most comprehensive study of total surface area in rooms appears in a government report by Hodgson et al.[13] They measured all objects larger than 300 cm^2 (about the surface area of a soda can) in 33 rooms in nine residences, encompassing 12 bedrooms that also functioned as offices, 12 common areas that included kitchens, dining rooms, living rooms, and hallways, seven bathrooms, and two rooms used exclusively as offices. Considering the "ventilated" air volume of each room by subtracting the volume of large objects, they reported surface-to-volume ratios of the rooms ranging from 2.3 to 5.7 m^{-1}. The ratios for bathrooms and offices were higher, on average, than for common areas and bedrooms. Mueller et al.[4] calculated the surface-to-volume ratio in four indoor environments: an aluminum odor test facility (5.3 m^{-1}), metal test rooms (stainless steel: 2.7 m^{-1}, aluminum: 3.3 m^{-1}), an office (2.8 m^{-1}), and a home (3.3 m^{-1}). These ratios included the surface area of the contents in each indoor environment. In a critique of the use of the deposition velocity in conceptual models, Nazaroff[5] assumed a "typical" S/V value of 2.8 m^{-1}. Many subsequent studies have used either Mueller's[4] ratios or Nazaroff's[5] "typical" value of S/V.

In addition to the surface area of the contents of a room, the type of material, dimensions, and orientation of the contents may also be important for certain processes. For example, the deposition velocity of a gas depends on its solubility in and reactivity with the surface.[14] Models of air flow dynamics may be used to understand indoor environmental quality, such as evaluating the effectiveness of heating, cooling, and ventilation systems in a building[15] or predicting personal exposure to pollutants. Realistic simulations of air flow indoors require accounting for the size, shape, and orientation of the objects in a room.

The objective of this research is to characterize the contents of three different types of rooms—bedrooms and kitchens in residences and offices in a university building—in terms of exposed surface area, volume, shape, and material composition. We select bedrooms and offices for measurement because people spend large amounts of time in them, and we select kitchens because they are the site of cooking-related emissions of gases and particles that can affect indoor chemistry and health.[11, 16-18] We calculate surface-to-volume ratios including and excluding the contents present in the room. Although the roughness and porosity of indoor surfaces mediate the rate and extent of gas and particle transfer between the surrounding air and the surface, we simplify our measurements of surface area by excluding these two characteristics, choosing to focus on the scale at which we are able to make measurements. We do catalog the surface material so that future studies may concentrate on roughness and porosity in more detail. Results of this study can be used to improve models of the transport, transformation, and fate of gases and particles in indoor air.

Experimental

Indoor environments

We considered three different types of rooms that are frequently modeled in studies of indoor environments: bedrooms, kitchens, and offices. Through a convenience sampling approach that aimed to capture diversity in building style and age of residences, we selected for analysis 10 bedrooms and nine kitchens in nine residences in Blacksburg, Virginia, that were built between 1941 and 2003. Of the residences studied, one was in a structure with >20 units, one was in a structure with 10-19 units, and seven were single-unit, detached structures. The distribution of the sample in terms of year built and number of units in the structure was reasonably representative of that in the American Housing Survey of 121 million housing units in 2017,[19] as shown in Fig. S1. We also measured three offices with different layouts in a university building at Virginia Tech.

Experimental metrics

We defined the surface area of a room excluding its contents as S (i.e., walls, floor, and ceiling only), the surface area with contents as S^*, the nominal volume of the room as V, equal to length (L) × width (W) × height (H) for rectangular cuboid rooms, and the volume minus the contents of the room as V^*. For irregularly shaped rooms and those with slanted ceilings, we subdivided the space into rectangular and triangular prisms, applied the appropriate geometric equation to calculate the volume of each section, and summed the volumes. Using these definitions, we calculated four metrics: (1) ratio of total surface area with contents to surface area without contents (S^*/S), ratio of volume minus contents to nominal volume (V^*/V), (2) ratio of surface area to volume without contents (S/V), and (4) ratio of surface area to volume with contents (S^*/V^*). If the room has no contents, then S^* equals S, and the ratio S^*/S equals 1, and likewise for V^* and V. If the contents of the room have the same amount of surface area as the walls, floor, and ceiling, then S^*/S equals 2. As ceiling heights are usually similar across different types of rooms, if no contents are present in a room, a smaller room (in length and width) will have a larger S/V compared to a larger room.

Surface area can vary with measurement resolution. For example, we could measure the surface area of a rectangular carpet as the projected $L \times W$, but we could also consider the surface area of each piece of yarn or even of each fiber making up the yarn. We employed a resolution of ~1 cm in our measurements, or what could readily be discerned using a measuring tape. While some processes of interest involve individual molecules, in which case nanoscale resolution would be most appropriate, it is not feasible at this stage to measure surface area in a room at this scale. Because smaller scale surface features will usually reside in the boundary layer, they are not expected to impact air flow patterns in a room, but they could affect the thickness of the boundary layer and thus impact gas and particle transfer between the bulk air and the surface.

Measurement techniques

We measured the dimensions of walls, floors, ceilings, and individual contents of the room using a measuring tape. Most of the kitchens were open on at least one side, where we defined the boundary according to an architectural feature, such as a change in flooring or partial wall. For rectangular prisms, we measured *L*, *W*, and *H* and used these to calculate surface area and volume. For cylindrical, conical, and spherical objects, we measured the diameter as well and used the appropriate equations to calculate surface area and volume. We applied the appropriate geometric equations where possible for other shapes. For irregularly shaped objects, we separated them into smaller 2D or 3D shapes, such as rectangles, triangles, or cones, applied the appropriate geometric equation to estimate the surface area and volume of each part, and then summed the parts. We only calculated the exposed surface area of objects, meaning the area which was in direct contact with the bulk air in the room. For example, if a box was on the floor, we did not calculate the surface area of the bottom of the box. We were unable to calculate the volume of some small items with surface area less than ~100 cm^2 (about the same as a billiard ball), due to their highly irregular shapes.

We also recorded the shape and the material of all objects. For those consisting of more than one material, we calculated the surface area of each different material separately. We categorized the shapes as either cylinder, flat, open top container, rectangular prism, sphere, or irregular. We categorized the materials as either cardboard, concrete, fabric or fiber, glass, metal, paint, paper, plastic, wood (stained), or other. All the closets, drawers, and cabinets in the rooms were closed, and thus, we did not measure the surface area of the objects inside them.

Statistical analysis

We compared S^*/S, V^*/V, S/V, and S^*/V^* among the three types of rooms using ANOVA. In addition, we performed a Shapiro-Wilks test to verify that the data points were normally distributed. We produced a normal quantile-quantile plot to visually evaluate the distribution of the data. We used an alpha of 0.05 for all statistical tests.

Results

We measured a total of 22 rooms listed in Table S1. These included 10 bedrooms and nine kitchens in residences and three offices in a university building. The rooms contained 26 to 81 measureable objects, including walls, floor, and ceiling as one object each. Nine of the bedrooms contained a bed consisting of a frame, mattress, linens, and pillows and a closet. The other bedroom contained a futon instead of a bed and did not have a closet. Other typical bedroom contents, such as tables, chairs, posters, cabinets, fans, storage boxes, and books, were present in variable quantities among bedrooms. All bedrooms had at least one window.

All kitchens contained a sink, refrigerator, oven, stove, microwave oven, and cabinets. All had a garbage can, which was located inside a cabinet or drawer in some cases. Some kitchens contained an eating area with a counter or dining table and chairs, along with additional contents such as stools, a pantry, and a toaster oven. The kitchens typically had only two or three walls and were open to other rooms in the residence. Not all kitchens had windows.

All three offices contained desks, chairs, computers, multiple shelves, cabinets, books, and common office supplies. Although all offices analyzed were located in the same building, they varied in size and style. In two of the offices, one of the walls was composed primarily of windows, while the third office did not have any windows. The third office was shared by three people and had three desks, three chairs, and multiple shelves.

Among all rooms studied, the length and width ranged from 1.7 m, in the case of the smallest kitchen, to 6.1 m, in the case of the largest bedroom, as shown in Table S1. The ceiling height ranged from 1.4 (one side of an attic bedroom with a slanted ceiling) to 3.4 m (one side of a kitchen with a vaulted ceiling) and was 2.4 or 2.7 m for most rooms. The volume of the rooms ranged from 9 to 50 m^3. On average, kitchens were smaller in volume than bedrooms and offices but had the largest variability in volume. Among the three types of rooms, bedrooms had the least variability in volume, with a relative standard deviation of 23% compared to 48% for kitchens and 26% for offices.

Surface area without contents, S, ranged from 22 to 86 m^2, as shown in Table S1. Typically, rooms with larger volume had larger S, although this was not always true. The surface area with contents, S^*, ranged from 36 to 146 m^2. In most cases, rooms with a larger S also had a larger S^*. While kitchens were only 6% smaller than bedrooms by volume V, on average, the difference in surface area was greater: S and S^* were 25 and 26% lower, on average, for kitchens. The lower surface area of the kitchens in this study largely arose from their open floor plans, so they had one or two fewer walls than did bedrooms, all of which were cuboidal with four walls and a door.

Table 1 summarizes metrics of surface area and volume for different room types and for all rooms combined. The ratios S^*/S, S/V, and S^*/V^* were not significantly different by room type, while the ratio V^*/V was lower for kitchens compared to bedrooms and offices. S^*/S averaged across all rooms was 1.5 ± 0.3 (standard deviation). The ratio was more variable for kitchens than for bedrooms, probably because some of the kitchens were partially open to the rest of the house, with walls or parts of walls absent. The two smallest kitchens in terms of volume had the highest ratio of S^*/S. Their additional surface area beyond the walls, floor, and ceiling, or $S^* - S$, fell near the mean and near the upper end of the range for all kitchens. There was no correlation between the amount of surface area of items in the kitchen and the room's nominal volume ($R^2 = 0.03$). Across all rooms, V^*/V fell in the range 0.70 to 0.97. The ratio for kitchens was lower than for other rooms because kitchens tended to have large cabinets and/or appliances. The ratio S/V

ranged from 1.3 to 2.5 m^{-1}, and the mean across all rooms was 1.8 m^{-1}. As accounting for contents increases the surface area and reduces the volume compared to an empty room, S^*/V^* was larger, ranging from 2.0 to 6.8 m^{-1} with a mean of 3.2 m^{-1}, which was 78% higher than the ratio without contents.

Table 1. Surface area without (*S*) and with (*S**) contents, volume without (*V*) and with (*V**) contents, and ratios for 10 bedrooms, nine kitchens, and three offices (average ± standard deviation).

Room	Surface Area (m^2)			Volume (m^3)			Surface Area-to-Volume Ratio (m^{-1})	
	S	S*	S*/S	V	V*	V*/V	S/V	S*/V*
Bedrooms	60 ± 11	86 ± 17	1.4 ± 0.2	31 ± 7	29 ± 7	0.93 ± 0.03	2.0 ± 0.2	3.0 ± 0.4
Kitchens	45 ± 15	64 ± 20	1.4 ± 0.4	29 ± 14	25 ± 14	0.8 ± 0.1	1.7 ± 0.4	3.2 ± 1.8
Offices	70 ± 15	125 ± 22	1.8 ± 0.1	38 ± 10	35 ± 10	0.93 ± 0.03	1.9 ± 0.1	3.6 ± 0.4
All	56 ± 16	82 ± 27	1.5 ± 0.3	31 ± 11	28 ± 11	0.9 ± 0.1	1.8 ± 0.3	3.2 ± 1.2

Fig. 1 shows that in terms of shape, the majority of surface area in the rooms, except for three of the kitchens, was a flat surface. Besides the walls, floor, and ceiling, other flat surfaces included cabinets, closet doors, and windows. The second most common shape was a rectangular prism, usually dominated in bedrooms by the bed, shelves, cabinets, and storage boxes. In kitchens, the microwave, oven, and refrigerator were counted as rectangular prisms. In offices, the majority of surfaces were also flat; however, more of the surface area was associated with irregularly shaped objects than with rectangular prisms.

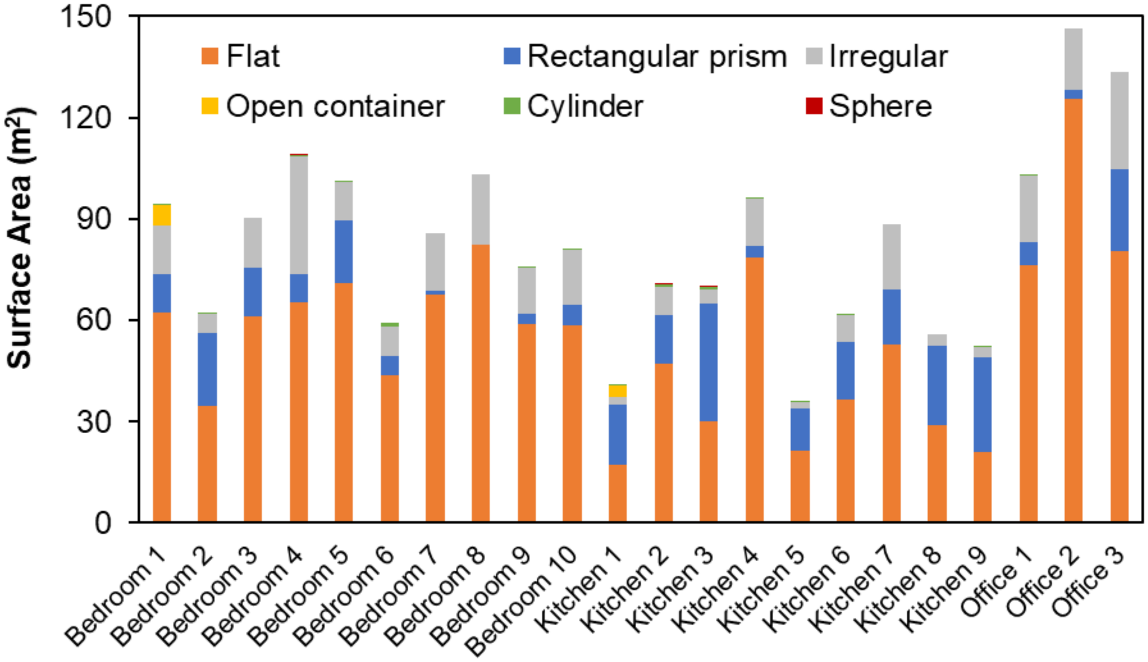

Fig. 1. Surface area by shape of all contents in each room.

Paint-covered surfaces were typically the most common type of material present in the rooms, as shown in Fig. 2, largely due to walls and ceilings. Painted surfaces accounted for 42 ± 14% of total surface area in a room. The floor was usually either made of fibrous material (i.e., carpet), stained wood, or plastic. In some cases, such as bedroom 3, stained wood was the most common material, as parts of the walls and the ceiling had wood paneling. Averaged across all rooms, stained wood was the second most common material, accounting for 22 ± 12% of total surface area. Plastic and metal were more common in kitchens and offices than in bedrooms. Many of the miscellaneous contents were comprised of plastic, glass, fabric, metal, or other materials, although most of these contents were relatively small in size and did not significantly influence the overall material composition.

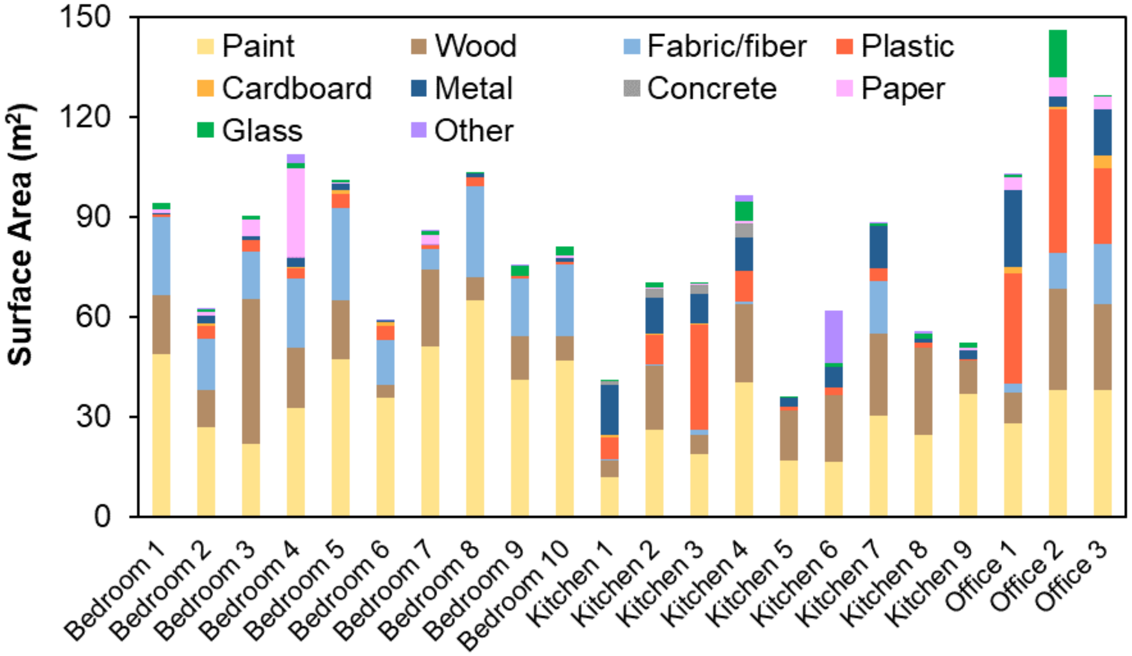

Fig. 2. Surface area by material of all contents in each room. "Paint" refers to paint-covered surfaces, and "Wood" refers to stained wood.

Discussion

In considering interactions between gases, particles, and surfaces indoors, we must consider the contribution of a room's contents to surface area. The average S^*/S ratio of 1.5 determined in this study means that objects in a room increase its surface area by 50% beyond that of the walls, floor, and ceiling alone. The average V^*/V ratio of 0.9 means that objects in a room decrease the volume of bulk air by 10%; they ranged from 3% to 30% of the total volume of the room. S^*/S and V^*/V were less variable than S^*/V^* (relative standard deviations of 20%, 11%, and 38%, respectively), so we recommend that researchers who wish to apply the results of this study first determine S and V for their scenario, then estimate S^* and V^* using the ratios shown in Table 1, and finally use these to calculate S^*/V^*. Our overall mean S^*/V^* ratio was 14% higher than the "typical" value of S/V used by Nazaroff et al.[5]

As the large furnishings or appliances were similar across rooms of the same type, we found that variability in surface area was attributable mainly to miscellaneous contents. By definition, a neat room would have more open space and more organized contents than would a messy room. A guest bedroom may have fewer miscellaneous contents in addition to the essentials (bed, closet, lights, etc.), whereas a child's bedroom may be less organized with more miscellaneous contents. Typically, a messy room would have a higher S^*/S ratio. In addition to size and shape, the orientation of the contents can affect the amount of exposed surface area in a room. For example, the exposed surface area of rectangular box with a high aspect ratio changes when the box is flipped on its side.

The S/V and S^*/V^* ratios calculated in this study are consistent with those in the literature, as summarized in Table 2. In previous studies of rooms in actual residences, the surface-to-volume ratio, accounting for large furnishings at least, ranged from 1.6 (averaged across 43 living rooms in Lee et al.[3]) to 5.4 m^{-1} (a bathroom in Hodgson et al.[13]), compared to our range of 2.0 to 6.8 m^{-1} (Table S1). Compared to a similar study by Hodgson et al.,[13] our S^*/V^* ratio was 14% lower for bedrooms, and our overall S^*/V^* ratio for all types of rooms, 3.2 m^{-1}, was only 3% lower than theirs of 3.3 m^{-1}, excluding bathrooms. The categorization and types of rooms differed from those described by Hodgson et al.[13] All of the bedrooms in their study also functioned as an office for the occupants, and the two offices were in residences. In our study, all bedrooms primarily functioned as bedrooms, and only four out of 10 contained a desk and chair. The offices in our study were in an academic building. Hodgson et al.[13] included kitchens as part of the common area, which also included living and dining rooms, hallways, and foyers, whereas our study focused on kitchens separately from all other common areas. One difference between this approach and Hodgson et al.'s[13] is the handling of small objects. Hodgson et al.[13] grouped small objects, between 300 and 2000 cm^2, into three size bins and counted them instead of measuring each object's dimensions. In addition, they did not measure small miscellaneous objects, less than 300 cm^2, approximately the size of soda can, while we omitted some objects that were smaller than ~100 cm^2.

The good agreement between the two studies suggests that the results from a combined 55 rooms in the San Francisco Bay Area and Blacksburg, Virginia, may be broadly representative. Even though there are regional differences in the housing stock across the country in terms of age and type of construction, such differences probably matter less for the objects that people keep in their rooms. One limitation of our sample is that the room occupants were mostly university students and faculty, and it is possible that there are demographic differences in how people furnish their rooms.

Table 2. Surface-to-volume ratios of indoor environments in other studies, grouped by type of room and whether contents were included.

Year	Author	Room type	Contents included	Surface-to-volume ratio (m^{-1})
1983	Bruno[20]	Conceptual	No	1.8
1990	Febo et al.[21]	Conceptual	N/A	0.5 – 5.0
1993	Nazaroff et al.[5]	Conceptual	Large furnishings	2.8
1994	Reiss et al.[22]	Conceptual	Large furnishings	2.8 and 3.3
2001	Thornburg et al.[23]	Conceptual	No	1.75
1989	Hayes[24]	Conceptual house	No	1.8
		Conceptual office	No	0.9
1973	Sabersky et al.[25]	Experimental chamber	No	4.1
1997	Fogh et al.[26]	Experimental room (4)	No	1.69 ± 0.25
2002	Thatcher et al.[27]	Experimental room	No	2.4
		Experimental room	Yes	3.2
1973	Mueller et al.[4]	Aluminum odor chamber	No	5.25
		Aluminum test room		3.3
		Stainless steel test room		2.69
		Commercial office	Large furnishings	2.82
		Bedroom	Large furnishings	3.3
2007	Singer et al.[28]	Furnished chamber	Yes	2.5
		Subset of rooms in Hodgson et al.[13]	Yes[a]	3.9 ± 0.7
1986	Nazaroff et al.[29]	House	N/A	2
		Art gallery	No	1.2
1999	Abt et al.[30]	House (3)	No	1.71 ± 0.08
2010	Scheff et al.[31]	Middle school	N/A	2
1999	Lee et al.[3]	Living room (43)	Large furnishings	1.6 ± 0.4
2003	Chao et al.[2]	Residence (6)	Large furnishings	2.4 ± 0.2
2006	Hussein et al.[32]	Entrance hall	Large furnishings	2.1
		Living room	Large furnishings	3.3
		Kitchen	Large furnishings	2.7
2005	Hodgson et al.[13]	Bedroom/office (12)	Yes[a]	3.5 ± 0.8
		Common room (12)	Yes[a]	2.8 ± 0.3
		Office (2)	Yes[a]	4.7 ± 0.1
		Bathroom (7)	Yes[a]	5.0 ± 0.3

[a] All furnishings and miscellaneous contents larger than 300 cm^2 included, and volume is the “ventilated” volume.

These results have important implications for understanding the chemistry of indoor environments. Accurate representation of pollutant deposition to surfaces is important for predicting reactions that may take place on surfaces and health effects because deposition eliminates the inhalation exposure route. Previous work has demonstrated that deposition of gases and particles depends on both surface area and type of material. A study of particle losses indoors showed that the deposition rate of submicron particles was ~2 times higher in a furnished experimental room compared to an unfurnished room;[27] the furnishings increased the surface area by a factor of 1.3, less than the average increase of 1.5 reported here. Surface deposition velocities for ozone, nitrogen dioxide (NO_2), and sulfur dioxide (NO_2) vary with material by a factor of 100 or more and were found to be zero for NO_2 and SO_2 on glass.[25, 33] A further complication is that films of water or semi-volatile organic compounds may coat the surfaces.[5, 34, 35] Laboratory experiments have shown that the reaction probabilities of ozone with Δ^3-carene and d-limonene, two monoterpenes that may be released from air fresheners, personal care or cleaning products, and wood, vary by a factor of 3-10 across three different materials: glass, polyvinylchloride, and zirconium silicate.[36] Gas-surface partitioning depends on material; the partition coefficient of di-2-ethylhexyl phthalate, a suspected endocrine disruptor, has been shown to vary by a factor of 20 between acrylic and steel.[11] These examples emphasize the importance of properly characterizing the total surface area of indoor environments, as demonstrated in an investigation of the impact of ozone-surface reactions on indoor air quality.[37]

In this study, we did not account for any of the contents present inside the closets, drawers, and cabinets because we assumed that the air-exchange rate between the bulk air inside the room and the air inside the closed space was much lower than that of the bulk air with outdoor air. If any of the closets, drawers, or cabinets were open, S^*/V^* would increase since the objects present within them would increase the amount of surface available for interactions with particles and gases in the bulk room air. Although small open cabinets or drawers may only increase S^*/V^* slightly, an open walk-in closet could produce a significantly higher ratio. Similarly, we did not account for humans present in the room. The surface area of an average human[38] is 1.70 m^2, which is negligible compared to the observed values of S^*. However, if several people were present in a room, such as in a classroom or during a social event, their surface area could raise S^*/V^* substantially. Whether surfaces are oriented vertically or horizontally, and particularly upward-facing, is important for particle deposition,[39] but we did not categorize orientation in this study.

Heating, ventilation, and air conditioning (HVAC) systems, which present surface area beyond the occupied space, can also impact transport, transformation, and fate of pollutants in indoor air. For example, residential HVAC filters have been shown to remove 10% of ozone from air flowing through the system, and even more is removed by deposition to ducts.[40] For a single room, the surface area presented by ducts is small (<1% if we assume a 6-inch duct that is five times the length of the room), but the surface area of filters and heat exchangers in the HVAC system could substantially increase the surface-to-volume ratio of a building. Additional measurements are needed to characterize fully the surface area of HVAC systems in buildings.

We measured surface area at a resolution of ~1 cm, much larger than the scale pertinent to gases and particles. Measuring objects with higher resolution would produce much larger values of S^* and S^*/V^*. Using atomic force microscopy with a resolution of ~5 nm, we previously showed that the surface area of smooth, flat materials including glass, aluminum, plastic, and stainless steel was up to 2.1 times higher than the projected surface area.[11] A study using a surface topography approach concluded that the “real” surface area of selected materials (vinyl, wallpaper, chipboard, plywood, plaster, and concrete) was up to 1.04 times higher than the projected area.[41] The difference would be much higher for "rougher" materials, especially fibrous ones such as carpets. If the surface roughnesses of all materials in a room were known, one could combine them with geometric surface area measurements to estimate total surface area. Clearly, measurement resolution has a sizeable impact on estimates of surface area and should be considered carefully in future studies. However, the projected surface area remains relevant because most experiments to determine deposition velocities use it. Roughness is especially important when considering adsorption on surfaces, and it also affects the deposition velocity of particles.[41, 42]

Measuring all the contents of a room is time-consuming and tedious (4-8 hours per room in this study), so the question arises, "How many items do we need to measure to capture most of the surface area?" Figure 3 shows the cumulative surface area in each room as a function of the number of items ordered from largest to smallest in terms of surface area. The number of items that contribute to 95% of the exposed surface area ranges from 14 to 26. Measuring 20 items captures at least 90% of the surface area, and measuring 25 items captures at least 95% of the surface area. In this enumeration, each wall, the floor, and the ceiling count as a different object, so these would account for six objects in a typical room. As volume incorporates another dimension, the smaller objects are even less important in estimating the total volume of objects in a room to calculate the volume of bulk air. Very small items, even if highly reactive, will not contribute much to overall deposition. Another labor-saving approach might be to use image processing or Light Detection and Ranging (LIDAR) to measure surface area, although these would require considerable method development.

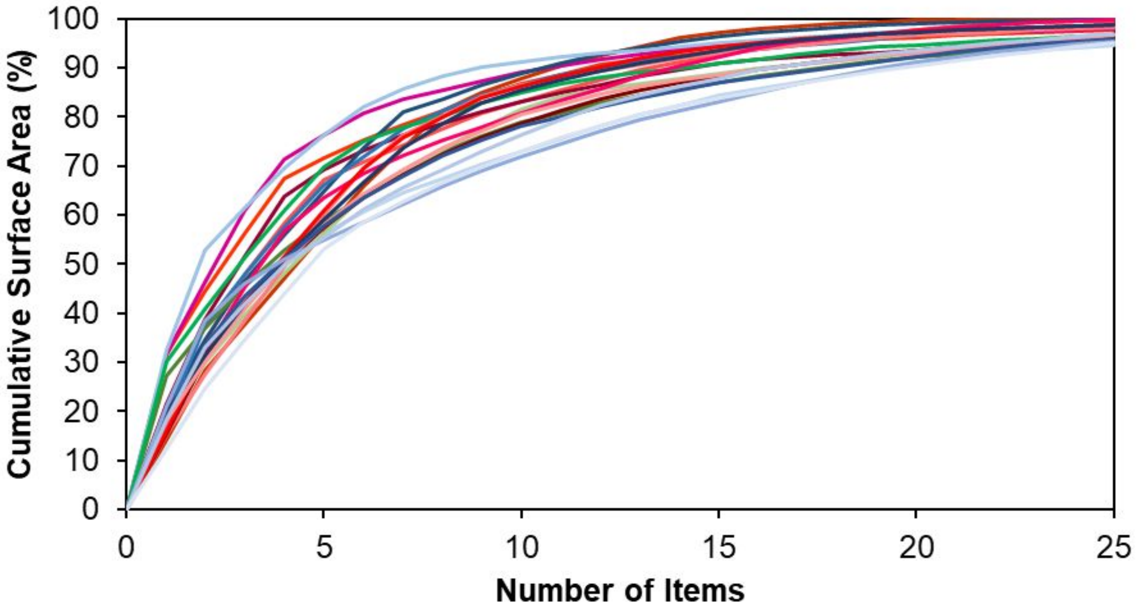

Figure 3. Number of items, including floor, ceiling, and each wall, required to achieve a certain amount of the total exposed surface area. Red is bedrooms, blue is kitchens, and green is offices. The dashed line indicates 90% of the total surface area.

Conclusions

We measured the surface-to-volume ratio, including and excluding contents, of 10 bedrooms, nine kitchens, and three offices, in buildings in Virginia. Across all types of rooms, the average ratio of surface area with contents to that without, S^*/S, was 1.5 ± 0.3 (mean ± standard deviation), meaning that the contents of a room contributed to the total surface area another 50% beyond the area of the walls, floor, and ceiling. The average ratio of volume of bulk air to volume of the entire room, V^*/V, was 0.9 ± 0.1, meaning that the contents occupied only about 10% of space in a room. S/V was 1.8 ± 0.3 m^{-1}, and S^*/V^* was 3.2 ± 1.2 m^{-1}, 80% higher compared to the ratio that ignores contents. These ratios were not significantly different by type of room, except for V^*/V, which was smaller for kitchens. Generally, the amount of miscellaneous contents beyond major furnishings and appliances dictated *S**/*V**, and more cluttered rooms, of course, had a higher *S**/*V**. While these measurements contribute new information about surface area indoors, they underestimate the true surface area that is accessible to gases and particles, as we necessarily used a resolution of ~1 cm. The largest 14-26 objects in a room accounted for 95% of its total surface area.

We also characterized the shape and material of objects in the rooms. The majority of objects were flat surfaces, dominated by walls, floor, ceiling, cabinets, closet doors, and windows. Paint was typically the most common surface type, largely due to walls and ceilings. This work will help improve the representation of surfaces in the indoor environment, and results can be used to improve models of the fate and transport of gases and particles in indoor environments.

Conflicts of Interest

There are no conflicts to declare.

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TOC Entry

Objects in a room add 50% to its surface area beyond the walls, ceiling, and floor.