Thermal Comfort Assessment of Conventional and High-Velocity Distribution Systems for Cooling Season

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ABSTRACT

Field measurements were taken to determine the thermal comfort conditions in the conditioned space of a residence using a conventional forced-air and high-velocity distribution systems. This assessment included whole-house testing. During the cooling season, measurements were made to evaluate the thermal comfort in the space by evaluating the air and radiant temperatures, relative humidity, and airflow rate. Results revealed that both systems maintain the majority of the house at comfortable conditions according to the predicted mean volt (PMV) and predicted percent dissatisfied (PPD) values, but higher comfort percentages were obtained using the high velocity distribution system. The conventional system register location had a significant effect on the comfort in the conditioned space.

INTRODUCTION

The study objective was to evaluate the comfort level obtained using high-velocity and conventional distribution systems since the high-velocity system delivers higher airflow rate and is projected to remove more moisture than a conventional system. This study quantifies the comfort level of the two dissimilar distribution systems. A typical Habitat for Humanity house that is roughly 1150 ft^2 (106.9 m^2) was used as the test home, which is equipped with two 2-ton 10 SEER heat pump systems with single-speed fan and compressors. The conventional distribution system is attached to a packaged heat pump unit; the air handler and condenser unit are located outdoors. The high-velocity distribution system is connected to a split system; the air handler (specifically made to be compatible with any 2 to 3 ton condenser unit) is located in the attic and the condenser unit is outdoors. Conventional distribution systems typically operate at 500 to 600 ft/min at the register; the high-velocity system's manufacturer states that the system operates at up to 2,000 ft/min. The high-velocity system's air handler design incorporates features to isolate noise and vibration because of its higher airflow rate (assumed to be noisier than a conventional distribution system). Also, supply ducts are lined with spun-bond nylon to help dampen sound. These units were operated alternately to assess the thermal comfort maintained in the house during the operation of each.

ASHRAE (1992) and ISO (1984) define thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment." The manufacturer of the high-velocity air handler/distribution system asserts that the system removes 30% more moisture in the cooling mode than conventional systems because the air leaving the evaporator coil is colder (US 2002). Therefore, the study objective was to evaluate the comfort level obtained using both distribution systems. The level of thermal comfort in the test space was evaluated by using a model developed by Int-Hout (1990), which is based on the International Standard Organization (ISO) program (ISO 1984) but substitutes the effective temperature for the operative temperature because it includes humidity effects and is seen as a better temperature index. The model outputs two of the most utilized and accepted comfort indices for design and field assessment—PMV and PPD. From these indices, comfort percentages were computed for each space while using each heat pump system.

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TESTING PROTOCOL AND TECHNIQUE

An 1150 ft^2 (106.9 m^2) single-story house with a basement, located in Lenoir City, Tennessee, was equipped with two 2-ton heat pumps. One is a package unit (10 SEER) located outside with a conventional forced-air duct distribution system in the unconditioned basement. The other has a high-velocity distribution system and is a split system with the condenser unit (10 SEER) located outside and the air handler and distribution ducts located in the attic. The study was accomplished by performing field measurements using the distribution systems and heat pumps to assess the thermal comfort according to the test methods listed in Table 1. Instrumenting the house and performing a whole-house assessment of the heat pump systems and distribution systems (as shown in Figures 1 and 2) provided the desired measurements. The detailed thermal comfort tests (using test stands) were performed during a three-day period during August 2001 with similar outside air temperature.

The high-velocity distribution system has twelve 2-in. (50.8 mm) openings located in the ceiling (see Figures 1 and 8). The conventional distribution system has eight standard 4 ×10 in. (101.6 × 254 mm) floor registers (see Figures 1 and 7). Lengthening the flexible branch duct of the conventional distribution system and relocating it from the floor to other typical registers locations (wall and ceiling) allowed air handler location effects on thermal comfort to be evaluated. Four register positions (floor, high-wall, low-wall, and ceiling) were evaluated by positioning the flexible duct with attached diffuser (standard rectangular for floor and walls locations, round diffuser [8 in. (515.62 mm)] for the ceiling location) in the desired location.

The portable measurement system incorporates thermal comfort standards (ASHRAE 55-1981, ISO 7730, and ISO 7726) in its design. The system is patterned after one developed by Benton et al. (1990) under ASHRAE RP-462, A Field Measurement System for the Study of Thermal Comfort. Table 2 presents the test specifications. Thermal comfort measurements were performed for the whole house, once without walls installed (room partitioned off) and again, room by room, with walls installed. The house was constructed without interior walls. Removable walls were assembled and erected to do the room-by-room comfort measurement. The test apparatus consists of four stands, each having four heights (see Table 2) that contain thermocouples measuring air and globe temperatures and air velocity. For the room-by-room measurements, stands were positioned as shown in Figure 2 for a total of 32 sensor locations for bedrooms and 64 for the living room. For the whole house assessment without wall partitions, stands were positioned for large spaces, as shown in Figure 2, for a total of 64 sensor locations. A data logger was used to collect and store data that were later entered into a PMV and PPD spreadsheet model to compute the PMV and PPD for each sensor location. Then a comfort percentage was determined from the computed PMV and PPD data assuming that the position was satisfied if the PMV was between –0.5 and 0.5 and if PPD was less than 20%. To establish whether the alternative distribution system was comparable to conventional systems, the house's thermal comfort and distribution efficiency were computed.

TABLE 1
Performance Tests

Tests	Assessment and Analysis Methods
Air handler location effects	Thermal comfort (PPD and PMV)
Portable thermal comfort	PPD and PMV

Thermal Comfort Analysis

To quantify the level of thermal comfort in the test space conditioned with different distribution systems, two of the most utilized and accepted comfort indices for design and field assessment—PMV (predicted mean vote) and PPD (predicted percent dissatisfied)—were used. The PMV index predicts the mean response of a large group of people according to the ASHRAE thermal sensation scale. Fanger (1970) developed an equation that related the PMV to imbalance between the heat flow required for optimum comfort at the specified activity and the actual heat flow from the body in a given environment. Fanger also developed a method of relating PPD to the PMV where "dissatisfied" is defined as anyone not voting. Fanger's equations have been incorporated in numerous models developed by others for predicting the PPD and PMV. ISO standard 7730 (1984) recommends acceptable PMV limits to be between 0.5 and –0.5 to obtain an 80% comfort

TABLE 2
Thermal Comfort Instrumentation

Parameter Monitored	Height Above Floor	Instrument
Air temperature	9, 24, 43, 67 in. (0.23, 0.61, 1.09, 1.70 m)	T-type thermocouples
Globe temperature	9, 24, 43, 67 in. (0.23, 0.61, 1.09, 1.70 m)	T-type thermocouples inside black ball {0.09 ft (2.29 mm) diameter}
Air velocity	9, 24, 43, 67 in. (0.23, 0.61, 1.09, 1.70 m)	Omnidirectional anemometer transducers
Relative humidity (RH)	40 in. (1.02 m)	Humidity sensor

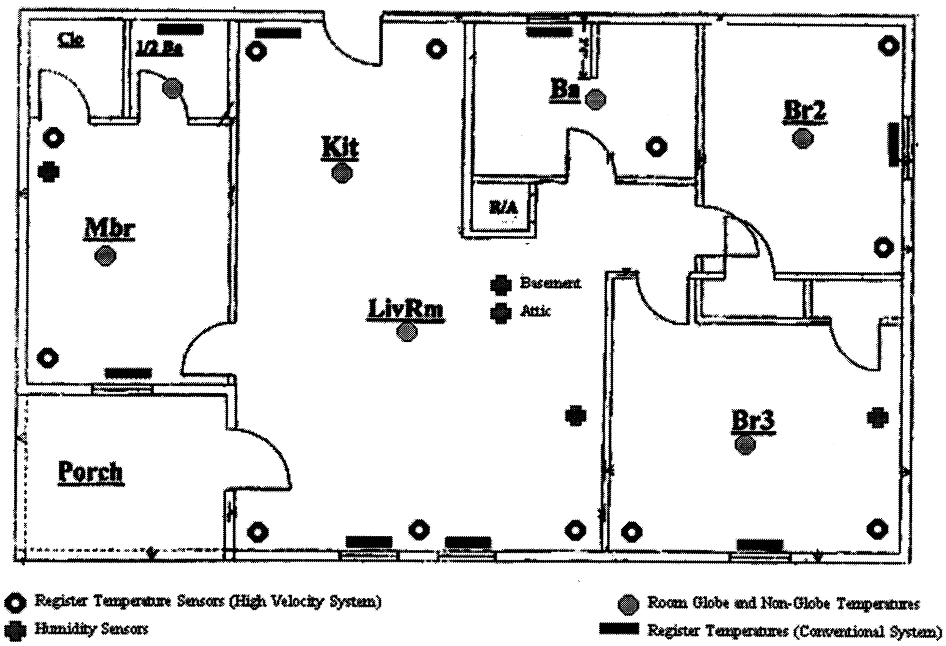

Figure 1 *Instrumentation of test house.*

level. The PPD assumes thermal neutrality (zero percent) is the optimum condition. The PPD is comparable to the PMV at a PPD less than or equal to 10%.

In this study, the PMV and PPD were computed from air temperature, mean radiant temperature, relative humidity, air velocity, metabolic rate, and clothing level incorporating most parameters recommended by ASHRAE (1992) and ISO (1985). A spreadsheet program and macros were used to derive time-averaged PMV and PPD values based on a model developed by Int-Hout (1990). Two comfort percentages were computed: one based on the PMV, the other based on the PPD. A rating of 75% indicates that the PMV was between ±0.5 at 75% of the locations and PPD was less than 10% at these locations. Comfort was determined using a typical clothing insulation level (clo equals 1—a trouser/skirt with suit jacket or sweater). One common home activity metabolic rate was evaluated, 19 Btu/h·ft^2 (58 W/m, 1 Met—seated, quiet). The relative humidity (RH) of the space without walls averaged 48.1% during the conventional system evaluation, as presented in Table 3. The air velocity and temperature were stratified, as shown in Table 4 and Figures 3 and 4. The standing height velocity varied more in the center of the house (positions 2 and 3, see Figure 2) reaching 70 fpm (0.36 m/s). The velocity averages were the highest in the living room at ankle and standing heights. The temperatures stayed within 6°F (3.3°C) high-velocity and 10°F(5.6°C) conventional bands, with the smallest band and lower temperatures occurring at position 1.

At the typical clo of 1 and Met of 1, 80% of the sensor locations were comfortable based on the PMV being within the comfortable range (–0.5 <> 0.5) and PPD being less than

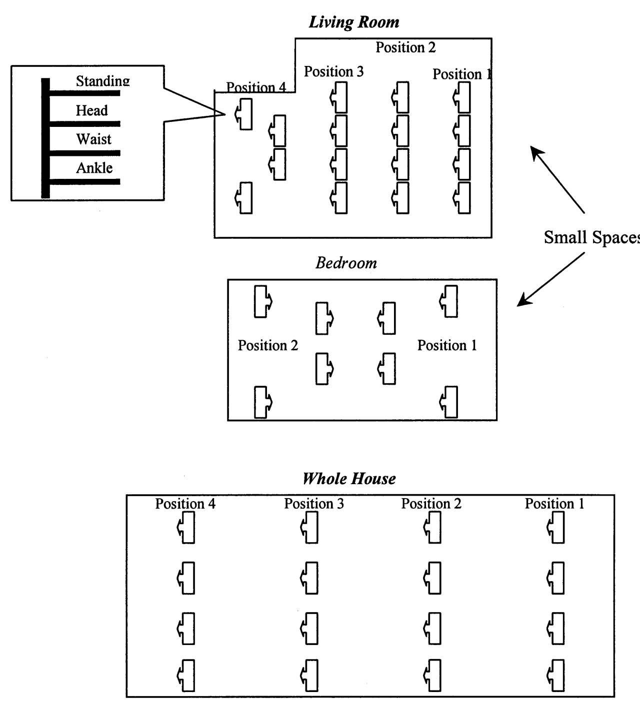

Figure 2 *Comfort stands setup (four test stands per position with four heights on each stand) during thermal comfort measurements. Living room stand position mirrors shape of living room.*

TABLE 3
Distribution System Comfort Rating (Conventional System)

Space Evaluated (Met 1, clo 1)	Averaged RH (%)	Based on PMV (±0.5)				Based on PPD (<10%) (%)			
		% Comfort	Max	Avg	Min	% Comfort	Max	Avg	Min
House—no walls	48.1	**80**	0.2	-0.2	-1.0	**80**	28.4	8.3	5.0
Bedroom 3	60.5	65.6	-0.1	-0.4	-1.0	65.6	28.2	9.7	5.5
Bedroom 2	49.5	100	0.4	0.2	0.0	100	7.8	6.0	5.0
Master bedroom	46	68.8	0.2	-0.4	-1.1	53.1	36.1	12.5	5.2
Living room	46.3	70.3	0.3	-0.4	-1.1	48.4	31.1	10.2	5.1
House—walls averaged		**76.2**				**66.9**			

TABLE 4
Air Velocity and Temperature (Conventional System)

Space	Averaged Air Velocity ft/min (m/s)				Averaged Air Temperature °F (°C)			
	V_{ankle}	V_{waist}	$V_{head, sitting}$	$V_{standing}$	T_{ankle}	T_{waist}	$T_{head, sitting}$	$T_{standing}$
House - No walls	21.7	15.8	15.7	29.1	70.6	70.7	64.5	64.5
	0.11	*0.08*	*0.08*	*0.15*	*21.4*	*21.5*	*18.1*	*18.1*
Bedroom 3	16.0	13.9	12.4	23.8	68.7	68.9	68.9	69.5
	0.08	*0.07*	*0.06*	*0.12*	*20.4*	*20.5*	*20.5*	*20.8*
Bedroom 2	15.2	9.7	11.6	2.6	72.6	72.8	73.1	73.7
	0.08	*0.05*	*0.06*	*0.01*	*22.6*	*22.7*	*22.8*	*23.2*
Master bedroom	14.5	12.2	15.6	18.0	68.3	69.8	70.5	71.6
	0.07	*0.06*	*0.08*	*0.09*	*20.2*	*21.0*	*21.4*	*22.0*
Living room	27.8	19.0	22.5	26.3	70.2	70.2	70.2	70.2
	0.14	*0.10*	*0.11*	*0.13*	*21.2*	*21.2*	*21.2*	*21.2*

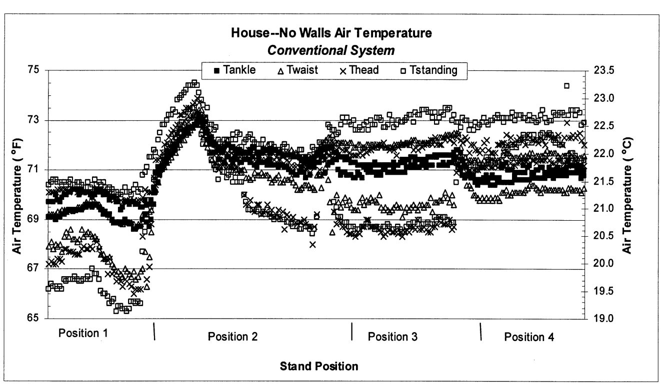

Figure 3 *Air velocity and temperature.*

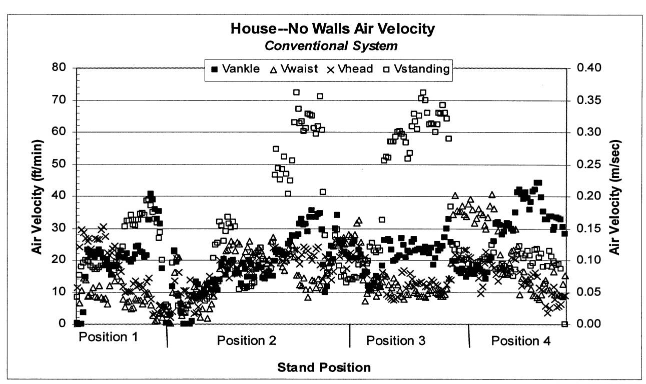

Figure 4 *Air velocity and temperature.*

TABLE 5
Distribution System Comfort Rating (High-Velocity System)

Space (Met 1, clo 1)	Averaged RH (%)	Based on PMV (±0.5)				Based on PPD (<10%) (%)			
		% Comfort	Max	Avg	Min	% Comfort	Max	Avg	Min
House—no walls	42.9	**92.2**	0.6	0.3	-0.2	**90.6**	13.8	7.0	5.1
Bedroom 3	46	96.9	-0.1	-0.2	-0.7	96.9	14.0	6.4	5.1
Bedroom 2	47.4	96.9	0.2	0.0	-0.6	96.9	11.8	5.6	5.0
Master bedroom	50.3	93.8	0.2	-0.2	-0.7	93.8	14.2	6.7	5.0
Living room	45.7	51.6	-0.3	-0.5	-0.9	48.4	22.3	11.2	6.4
House—walls averaged		**84.8**				**84.0**			

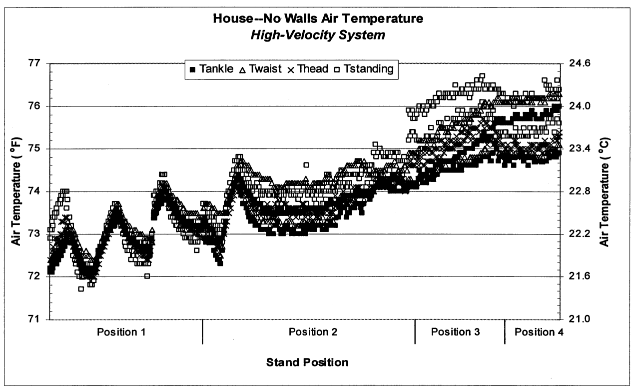

Figure 5 *House with no walls sample air temperature, ~1 hour/position (high velocity).*

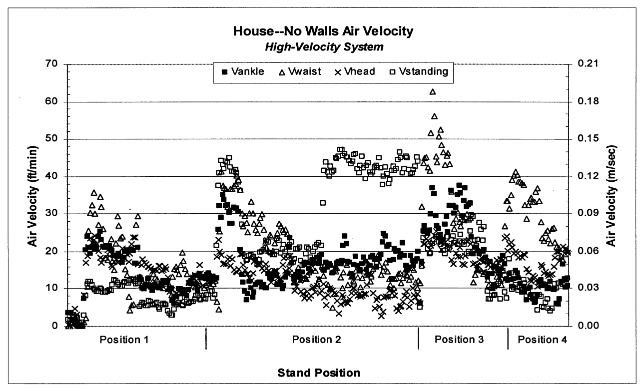

Figure 6 *House with no walls sample air velocity, ~1 hour/position (high velocity).*

10%, as indicated in Table 3. The locations that are uncomfortable are too cold because the minimum PMV value is –1.0 (at standing height). The averaged PPD is 8.3%, but some locations have a maximum of 28.4% dissatisfied. For the room-by-room analysis shown in Table 3, the comfort percentage ranged from 65.6% to 100% based on the PMV and 48.4% to 100% based on the PPD during the conventional system operation. The rooms not yielding a 100% comfort percentage were uncomfortable due to locations being too cold, as indicated by the minimum PMV being as low as –1.1. The PPD values for these rooms ranged from 5.1% to 36.1%, averaging 9.7% to 12.5%. Bedroom 2 has a 100% comfort percentage with the maximum PPD of 7.8% and PMV averaging 0.2. The averaged air temperatures (72.6°F [22.6°C] to 73.7°F [23.2°C]) in the room are at least 2°F (1.1°C) higher than any other room, which contributed to the room comfort rating.

During high-velocity system evaluation, the space without walls averaged 42.9% RH, as shown in Table 5. The RH is 10.8% less than that maintained using the conventional system. The air velocity is stratified as in the conventional system test, but the temperatures show less stratification than that of the conventional system, as shown in Figures 5 and 6. Position 4 reveals the greatest air temperature stratification, ranging within 3.2°F (1.8°C). The air velocity varied more in the center of the house (positions 2 and 3, Figure 2) similar to results obtained during the conventional system operation test. As indicated in Table 6, the velocity averages were the highest in the living room for all heights with the exception of the head-sitting position, which was the highest in bedroom 2. At the standard clo of 1 and Met of 1, 92.2% of the sensor locations were comfortable, with the PMV and PPD averaging 0.3% and 7%, as revealed in Table 5. The few uncomfortable locations would be too warm, as indicated by the PMV having a maximum of 0.6 (at head height). The room-by-room comfort percentages are greater than 90% except the living room. The above 90% comfort rooms have averaged PPD values ranging from 5.6% to 6.7%; the uncomfortable locations are too cold, as revealed by the PMV being as low as –0.7. The living room has a 51.6% comfort percentage because the room is too cold, having PMV value ranging from –0.9 to –0.3. The maximum PPD is 22.3% and the average air temperatures in the room are 1°F (0.6°C) to 4°F (2.2°C) below that of the other rooms (see Table 6).

Varying the register placement in bedroom 3 revealed that ceiling (96.9% comfort percentage) and wall (96.9% and 100% comfort percentage) register locations significantly improve the comfort percentages based on the PMV values, as seen in Table 7. The few sensor locations that are uncomfortable for the ceiling configuration are a mixture of being too warm (PMV maximum of 0.40) and too cold (PMV minimum of –0.8). The room air temperature averages were the highest for the ceiling configuration, as shown in Table 8, which may contribute to the warm locations. The high-wall uncomfortable locations are due to the cool areas in the room as indicated by the –0.5 minimum PMV value. For wall and ceiling configurations, the PPD averaged between 5.4% and 6.5%. The room air velocity averages (shown in Table 8) were the lowest for the low-wall configuration where the comfort percentage was the highest (100%).

CONCLUSIONS

The thermal comfort in an 1150 ft^2 (106.9 m^2) house equipped with conventional and high-velocity distribution systems was evaluated. Several conclusions were drawn from the thermal comfort results obtained in this field test study.

- Both systems maintained the majority of the house at comfortable conditions according to the PMV and PPD indices, but the high-velocity distribution system, on average, yielded higher comfort percentages for the whole-house with and without walls.
- Air distribution system register locations do affect the comfort conditions in the house according to PMV and PPD data. Floor location of registers had the lowest comfort level.

TABLE 6
Air Velocity and Temperature (High-Velocity System)

Space	Averaged Air Velocity ft/min (m/s)				Averaged Air Temperature °F (°C)			
	V_{ankle}	V_{waist}	$V_{head, sitting}$	$V_{standing}$	T_{ankle}	T_{waist}	$T_{head, sitting}$	$T_{standing}$
House—no walls	16.5	20.4	14.2	20.2	73.5	73.8	74.0	74.2
	0.08	*0.10*	*0.07*	*0.10*	*23.1*	*23.2*	*23.3*	*23.4*
Bedroom 3	12.9	17.7	17.8	15.4	70.5	70.6	70.8	71.1
	0.07	*0.09*	*0.09*	*0.08*	*21.4*	*21.5*	*21.6*	*21.7*
Bedroom 2	14.7	20.5	26.3	2.7	72.3	72.4	72.5	72.7
	0.07	*0.10*	*0.13*	*0.01*	*22.4*	*22.5*	*22.5*	*22.6*
Master bedroom	22.3	14.1	11.5	15.7	70.4	70.8	71.2	72.1
	0.11	*0.07*	*0.06*	*0.08*	*21.3*	*21.5*	*21.8*	*22.3*
Living room	22.6	27.5	22.7	22.7	69.1	69.0	69.3	69.4
	0.12	*0.14*	*0.12*	*0.12*	*20.6*	*20.5*	*20.7*	*20.8*

TABLE 7
Duct/Register Location Comfort Rating (Conventional System)

Space (Bedroom 3: Met 1, clo 1)	Averaged RH (%)	Based on PMV (±0.5)				Based on PPD (<10%) (%)			
		% Comfort	Max	Avg	Min	% Comfort	Max	Avg	Min
Floor—standard location	60.5	65.6	–0.1	–0.4	–1.0	65.6	28.2	9.7	5.5
Ceiling—center of room	46.1	96.9	0.4	0.1	–0.8	96.9	18.8	6.5	5.0
High wall—1.5 ft from ceiling	49.0	96.9	0.0	–0.2	–0.5	96.9	10.7	6.0	5.0
Low wall—2 ft from floor	51.2	100	0.1	–0.1	–0.3	100	6.8	5.4	5.0

TABLE 8
Air Velocity and Temperature for Duct/Register Location (Conventional System)

Space (Bedroom 3: Met 1, clo 1)	Averaged Air Velocity ft/min *(m/s)*				Averaged Air Temperature °F *(°C)*			
	V_{ankle}	V_{waist}	$V_{head, sitting}$	$V_{standing}$	T_{ankle}	T_{waist}	$T_{head, sitting}$	$T_{standing}$
Floor—standard location	12.9	17.7	17.8	15.4	70.5	70.6	70.8	71.1
	0.07	*0.09*	*0.09*	*0.08*	*21.4*	*21.5*	*21.6*	*21.7*
Ceiling—center of room	11.8	14.6	18.5	19.3	72.4	72.7	73.0	73.1
	0.06	*0.07*	*0.09*	*0.10*	*22.4*	*22.6*	*22.8*	*22.9*
High wall—1.5 ft from ceiling	10.7	14.8	18.1	21.3	70.5	70.7	71.0	70.9
	0.05	*0.08*	*0.09*	*0.11*	*21.4*	*21.5*	*21.7*	*21.6*
Low wall—2 ft from floor	8.8	7.2	7.2	10.2	70.2	70.6	71.3	72.1
	0.04	*0.04*	*0.04*	*0.05*	*21.2*	*21.5*	*21.8*	*22.3*

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