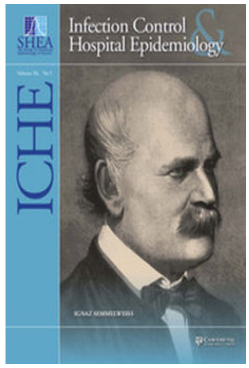

Do Peer Effects Improve Hand Hygiene Adherence among Healthcare Workers?

Mauricio N. Monsalve, Sriram V. Pemmaraju, Geb W. Thomas, Ted Herman, Alberto M. Segre and Philip M. Polgreen

Infection Control & Hospital Epidemiology / Volume 35 / Issue 10 / October 2014, pp 1277 - 1285
DOI: 10.1086/678068, Published online: 16 January 2015

ORIGINAL ARTICLE

Do Peer Effects Improve Hand Hygiene Adherence among Healthcare Workers?

Mauricio N. Monsalve, MS;[1] Sriram V. Pemmaraju, PhD;[1] Geb W. Thomas, PhD;[2] Ted Herman, PhD;[1] Alberto M. Segre, PhD;[1] Philip M. Polgreen, MD, MPH[3]

OBJECTIVE. To determine whether hand hygiene adherence is influenced by peer effects and, specifically, whether the presence and proximity of other healthcare workers has a positive effect on hand hygiene adherence.

DESIGN. An observational study using a sensor network.

SETTING. A 20-bed medical intensive care unit at a large university hospital.

PARTICIPANTS. Hospital staff assigned to the medical intensive care unit.

METHODS. We deployed a custom-built, automated, hand hygiene monitoring system that can (1) detect whether a healthcare worker has practiced hand hygiene on entering and exiting a patient's room and (2) estimate the location of other healthcare workers with respect to each healthcare worker exiting or entering a room.

RESULTS. We identified a total of 47,694 in-room and out-of-room hand hygiene opportunities during the 10-day study period. When a worker was alone (no recent healthcare worker contacts), the observed adherence rate was 20.85% (95% confidence interval [CI], 19.78%–21.92%). In contrast, when other healthcare workers were present, observed adherence was 27.90% (95% CI, 27.48%–28.33%). This absolute increase was statistically significant ($P < .01$). We also found that adherence increased with the number of nearby healthcare workers but at a decreasing rate. These results were consistent at different times of day, for different measures of social context, and after controlling for possible confounding factors.

CONCLUSIONS. The presence and proximity of other healthcare workers is associated with higher hand hygiene rates. Furthermore, our results also indicate that rates increase as the social environment becomes more crowded, but with diminishing marginal returns.

Infect Control Hosp Epidemiol 2014;35(10):1277-1285

Hand hygiene is a critical infection control measure.[1] Yet reported rates of adherence remain low.[2] Multiple reasons have been cited, including, for example, that healthcare workers (HCWs) do not understand the importance of proper hand hygiene.[3,4] Several work-related environmental factors have also been cited.[4]

Environmental factors contributing to lower adherence include a lack of sinks or alcohol-based hand hygiene dispensers in convenient locations.[3-6] The busyness of an environment may also affect rates.[4,7,8] For example, as HCWs' clinical loads increase, they may become less adherent. Institutional culture, specifically the importance that administrators place on hand hygiene,[9-12] may be another environmental factor related to hand hygiene rates.

In addition to traditional notions of the environment, some studies indicate that the behavior and/or presence of other people may also affect adherence. Some studies have indicated that the presence of a hand hygiene observer affects hand hygiene rates,[13-16] whereas other investigations demonstrate that a HCW is more likely to practice hand hygiene if they have recently observed another HCW practicing hand hygiene.[17,18]

The specific effects resulting from social pressure on behavior have been referred to as "social network effects" or "peer effects." For instance, researchers have identified smoking and obesity-related behavior to be influenced by peer effects.[19,20] Worker productivity also seems to exhibit to peer effects.[21] Thus, hand hygiene may also be influenced by peer effects in healthcare settings.

Our hypothesis is that the presence and proximity of other HCWs has a positive effect on hand hygiene adherence. For this study, we used a customized automated hand hygiene

Affiliations: 1. Department of Computer Science, University of Iowa, Iowa City, Iowa; 2. Department of Mechanical and Industrial Engineering, University of Iowa, Iowa City, Iowa; 3. Department of Internal Medicine and Department of Epidemiology, University of Iowa, Iowa City, Iowa.

Received February 3, 2014; accepted May 28, 2014; electronically published September 9, 2014.
This work was supported in part by a Cooperative Agreement from the Centers for Disease Control and Prevention. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the Centers for Disease Control and Prevention.

 0899-823X/2014/3510-0009$15.00. DOI: 10.1086/678068

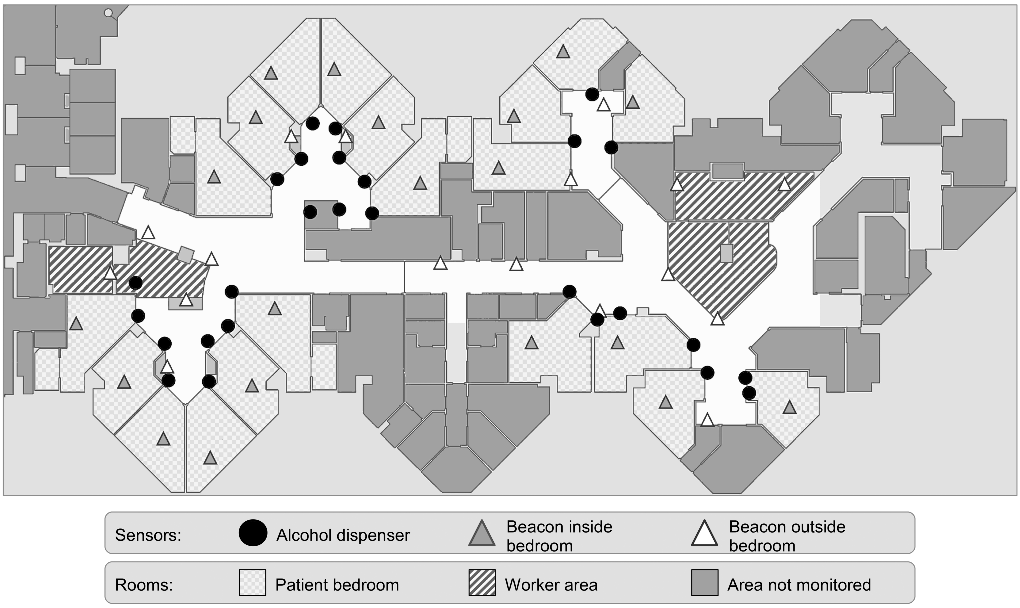

figure 1. Floor plan of the medical intensive care unit displaying the placement of the stationary sensors. Note that the worker areas consist of nurse stations and physician workrooms.

monitoring system that can (1) detect whether a HCW has practiced hand hygiene on entering and exiting a room and (2) estimate the location of other healthcare workers in the unit with respect to the HCW exiting and entering a room.

METHODS

Data Acquisition

As part of a process-improvement project to measure hand hygiene behavior, we deployed a wireless sensor network to measure interactions between HCWs (eg, close proximity contacts), their individual location (eg, "inside patient room," "in hallway," "at nurses' station") and hand hygiene activity (ie, alcohol dispenser usage) in the medical intensive care unit (MICU) of the University of Iowa Hospital and Clinics (UIHC) for 10 consecutive days. This sensor network consisted of small pager-sized wireless sensors or "motes." These programmable, battery-powered devices consist of a small processor with flash memory and an IEEE 802.15.4–compliant wireless radio. We programmed the motes to broadcast a brief message every 7–12 seconds. When received by other motes within range, these messages encode the unique identifier of the sender mote, the received signal strength index (RSSI) associated with the message (a proxy for distance, because RSSI increases with proximity), and the time that the

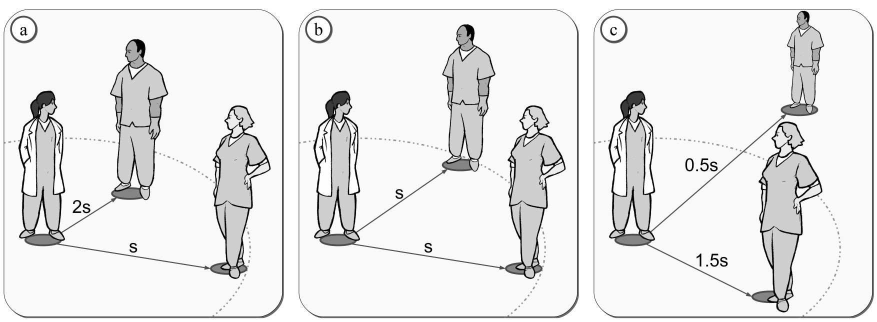

figure 2. The social variables W1M (number of encounters within 1 minute of the opportunity) and SRSSI (sum of received signal strength [RSSI] to peers at the moment of the opportunity) score the social context of a healthcare worker differently. Each inset below (*a*, *b*, and *c*) depicts a different social context around a focal worker (in white coat). Each arrow has an associated RSSI. The dotted circle represents the maximum distance at which an encounter is considered for W1M and is associated with an RSSI of 1 unit. The values for W1M and SRSSI in each inset are (*a*) W1M = 2 and SRSSI = 3 units, (*b*) W1M = 2 and SRSSI = 2 units, and (*c*) W1M = 1 and SRSSI = 2 units. Variation in one variable does not imply variation in the other.

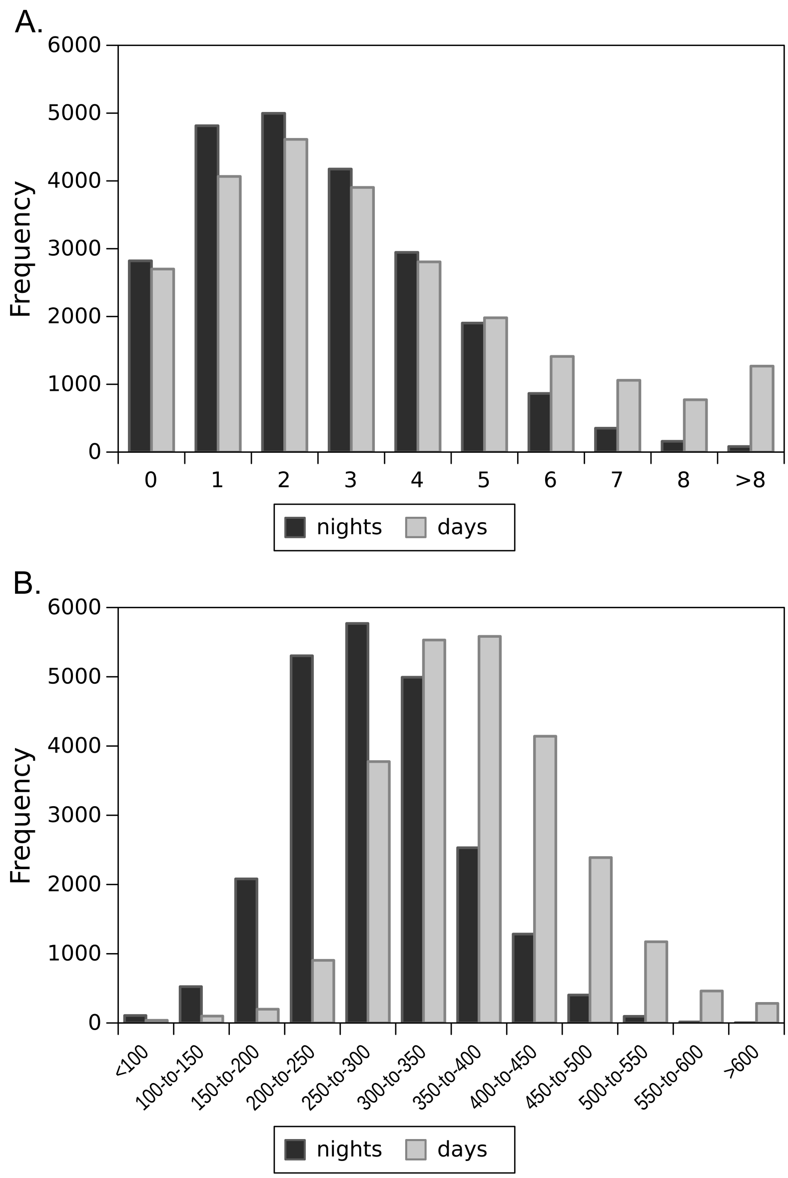

FIGURE 3. Distribution of social variables. *A*, W1M, the number of encounters within 1 minute of the opportunity. *B*, SRSSI, the sum of received signal strength to peers at the moment of the opportunity.

message was received. These data were recorded in the flash memory of the receiving mote for later analysis. The motes' radios communicated through an unused portion of the Wi-Fi spectrum to avoid interfering with medical equipment. More details of our approach have appeared elsewhere.[22-26]

Our sensor network consisted of stationary sensors or "beacons" and wearable sensors or "badges." Beacons were placed inside all 20 patient bedrooms as well as outside rooms (eg, in hallways and at nurses' stations) throughout the unit. This spatial grid of sensors served to locate workers in the unit from the collected data. Beacons also included instrumented alcohol dispensers that broadcast messages whenever their pumps were used. We only instrumented and considered alcohol dispensers located immediately outside every room, ignoring the dispensers sporadically located within patient rooms (Figure 1).

Badges were worn by HCWs and were collected from and distributed to workers at the beginning of each shift. HCWs were divided into 3 different job types: (1) doctors, including staff physicians, fellows, and residents; (2) nurses, including MICU nurses, nurse assistants, and nurse managers; and (3) critical care support, including clerks, pharmacists, and respiratory therapists.

Badges were assigned randomly to workers within each job type, ensuring that individual workers could not be identified, and workers could not be tracked across different shifts. This

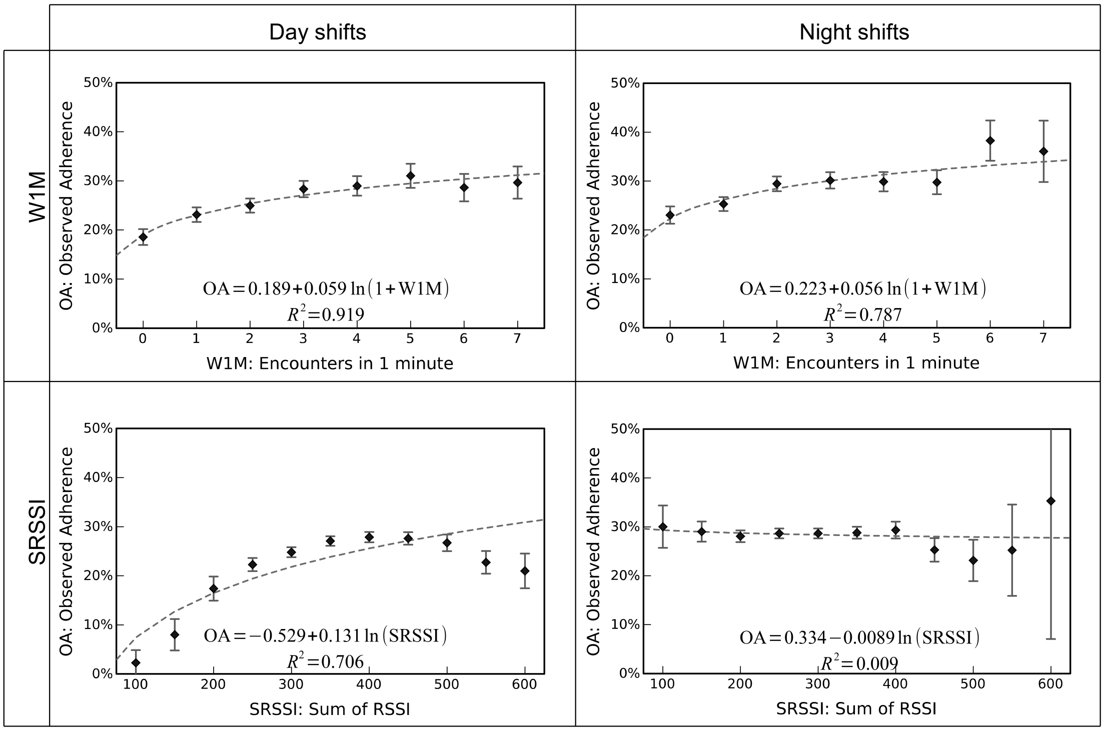

figure 4. Observed adherence rates (OAs) by social variable (SRSSI, sum of received signal strength [RSSI] to peers at the moment of the opportunity; W1M, the number of encounters within 1 minute of the opportunity) during day and night shifts. Each diamond represents an average adherence rate by social variable value (W1M) or bin (SRSSI, bins of width 100). The vertical bars represent the 95% confidence interval associated with the corresponding adherence rates. The dashed lines represent the adherence rate fit to the natural logarithm of the social variable (1 + W1M or SRSSI) using weighted regression (weighted on the inverse of the standard error). The logarithm of 1 + W1M fits the adherence rate well, demonstrating diminishing marginal returns with respect to that variable.

deployment was part of a process-improvement work, and no patient information was collected; it was ruled "non-human-subjects research" by the University of Iowa's institutional review board.

Measuring Hand Hygiene Adherence

For this project, we defined a "hand hygiene opportunity" as the event corresponding to a HCW entering or leaving a patient room. A central measure of our work is the "observed adherence," which we define as the fraction of opportunities associated with alcohol-dispenser activations, where both the opportunity and the activation correspond to the same individual. We associated an opportunity to an alcohol-dispenser activation if the 2 events occurred within 30 seconds of each other and were associated with the same badge (ie, the same HCW).

To accurately identify opportunities and dispenser activations, we processed the signals recorded by the sensors in a variety of ways.[22,23] Opportunity detection and attribution is difficult in situations when a worker enters a room briefly or is accompanied by several coworkers. Attributing dispenser activations is also difficult when several workers are close by or when there is a "false activation" (ie, an activation caused by a nonmonitored person). Our methods are governed by several "event detection" parameters that we tuned. In this article, we mainly report results obtained by tuning event detection parameters so as to maximize the number of dispenser activations that matched opportunities during night shifts. We used night shift data because these had fewest false activations.

Measuring the Social Context for HCWs

We developed 2 different scores to characterize the social context of HCWs.

Coworkers encountered within 1 minute (W1M). This measure represents the number of different coworkers encountered within an interval of 1 minute, centered on each hand hygiene opportunity. An encounter is considered to occur within a distance of approximately 4 m, which is approximately the distance at which a worker might be aware of coworkers.

Sum of RSSI (SRSSI). The RSSI of a message serves as a measure of spatial proximity between the communicating radios. For a worker's badge, we can use the sum of the RSSIs (decibel-milliwatts) of messages received from other badges as a measure of how crowded his or her social space is at the

TABLE 1. Hand Hygiene Statistics Disaggregated by Shift Type and Job Type

Variable	All	Critical care	Doctor	Nurse
Day shifts				
No. of workers	205	18	58	129
No. of opportunities	24,580	1,742	2,948	19,890
Average adherence, %	25.75	30.37	24.73	25.50
Average W1M	3.48	4.48	5.35	3.11
Average SRSSI	377.56	388.61	405.45	372.4
Night shifts				
No. of workers	114	10	21	83
No. of opportunities	23,114	1,238	926	20,950
Average adherence, %	28.51	23.99	28.73	28.76
Average W1M	2.72	2.39	3.7	2.69
Average SRSSI	284.1	231.79	283.04	286.72

NOTE. SRSSI, sum of received signal strength to peers at the moment of the opportunity; W1M, the number of encounters within 1 minute of the opportunity.

time of each hand hygiene opportunity. SRSSI increases as the worker gets closer to coworkers, and it also increases when other badged coworkers enter the sensing range.

Note that W1M provides a clear distinction between being "alone" ($W1M = 0$) and being "accompanied" ($W1M > 0$),[27,28] whereas SRSSI, a novel measure developed for this project, offers a smoother measure for the effect of the social context on adherence (Figure 2).

We measured the association between the social variables and adherence using weighted linear regression. The reciprocal of the standard errors were used as weights. To model the decreasing effect (diminishing marginal returns) of the social variables on adherence, we fitted adherence to the natural logarithm of W1M plus 1 and to the natural logarithm of SRSSI independently.

Controlling for Confounding Variables

Identifying a statistically significant association between the presence of more peers and higher hand hygiene rates does not necessarily entail causality; we may instead be observing the effects of unmeasured confounding variables. Confounding factors could be related to either HCWs or patients. First, considering HCWs, an individual workers' likelihood to closely adhere to hand hygiene recommendations and their social habits may introduce spurious associations between their social context and hand hygiene adherence. It could be that healthcare workers who are more hand hygiene adherent may be more likely to work with others more often. Another possibility is that HCWs who are more adherent may be more likely to be assigned to work in groups.

Second, considering patients, critically ill patients may be more likely to be cared for by multiple HCWs at once. Furthermore, critically ill patients may either motivate greater hand hygiene adherence (for reasons related to their illness) or less hand hygiene adherence (in case of an emergency). Thus, HCWs may show different hand hygiene adherence when caring for critically ill patients.

We attempted to control for these confounding factors by using a matched case-control analysis, matching opportunities by HCW and by patient. The identity of each worker was represented by the sensor badge worn by the worker and the shift number, because different workers could have worn the same badge during different shifts. The identity of each patient was represented by his or her room number and the shift number, because the same room may host different patients during different shifts.

We tested the presence of peer effects following the second approach described in Gabranth et al.[29] We reduced the matched clusters to pairs by averaging each social variable (W1M and SRSSI) in the adherence and nonadherence groups. We then performed a Wilcoxon matched-pairs signed-rank test to assess the significance of the increase.

RESULTS

Observed Adherence

We identified a total of 47,694 opportunities and 14,989 dispenser activations during the 10-day study period. Of these opportunities, 12,919 were satisfied (resulting in a hand hygiene event), yielding an observed adherence of 27.09% (95% confidence interval [CI], 26.69%, 27.49%). Adherence at entry was 25.94% (95% CI, 25.38%–26.50%), whereas adherence at exit was 28.23% (95% CI, 27.66%–28.80%). The social variable W1M (number of HCWs encountered in 1 minute) had an average 2.92 (day, 3.30; night, 2.52) and standard deviation of 1.71 (day, 1.81; night, 1.01). The social variable SRSSI had an average of 329.92 (day, 372.00; night, 285.16) and standard deviation of 92.55 (day, 86.70; night, 76.12). The distribution of both social variables is depicted in Figure 3. Unless stated otherwise explicitly, the results we report in this section are for event-detection parameter settings that maximize the number of dispenser activations that match opportunities in the night shift data.

TABLE 2. Observed Adherence of Healthcare Workers when Alone or in the Presence of 1 Coworker, Disaggregated by Job Type

Worker, coworker	Adherence, %	95% CI radius	Opportunities
Any			
None	20.85	1.07	5,521
Any	24.30	0.89	8,880
CCare	29.43	3.82	547
Doctor	24.03	3.43	595
Nurse	23.96	0.95	7,738
CCare			
None	18.07	4.78	249
Any	22.89	3.57	533
CCare	13.04	13.76	23
Doctor	31.25	16.06	32
Nurse	22.80	3.76	478
Doctor			
None	12.38	6.30	105
Any	20.13	4.52	303
CCare	42.86	25.92	14
Doctor	15.22	10.38	46
Nurse	19.75	5.01	243
Nurse			
None	21.15	1.11	5,167
Any	24.55	0.94	8,044
CCare	29.80	3.97	510
Doctor	24.37	3.70	517
Nurse	24.18	1.00	7,017

NOTE. Each adherence value is associated with its 95% confidence interval (CI) radius (symmetric CIs) and the number of opportunities in which it was observed (sample size). CCare, critical care.

Adherence Rates in the Context of Social Variables

When a worker was alone (no recent HCW contacts: W1M = 0), observed adherence was 20.85% (95% CI, 19.78%–21.92%). In contrast, we found that, when other HCWs were present (recent encounters of other HCWs: W1M > 0), observed adherence was 27.90% (95% CI, 27.48%–28.33%). This absolute increase of 7% is statistically significant, with an associated *P* value less than .001 (2-tailed *t* test).

We also found that observed adherence increased as HCWs were surrounded by more and more coworkers. Figure 4 shows that the adherence rate increases as the number of coworkers encountered (W1M) increases for both day and night shifts and that it also increases with SRSSI during the day shifts. However, SRSSI varies very little during the night, making it difficult to make statistical inferences using this variable during the night shift. All curves are consistent for adherence at entry and at exit. A diminishing marginal returns effect was found with the number of coworkers encountered: adherence increases with W1M, but with progressively decreasing increments. This can be seen by the positive coefficient associated with the W1M variable, which is on the log scale. With SRSSI, however, adherence decreases after a certain point.

Social Influence and Job Type

Table 1 shows our results disaggregated by shift type (day and night) and job type (doctor, nurse, and critical care). As one might expect, the values of social variables at night are smaller than during the day. However, observed adherence is slightly higher at night than during the day (28.51% vs 25.75%). The table also shows that nurses had higher observed adherence than doctors.

To measure peer effects by job types, we enumerated observed adherence of workers of each job type (1) alone and (2) in the presence of 1 coworker, also classified by job type (Table 2). The observed adherence of workers of any job type is consistently greater when they encounter someone than it is when they are alone. This effect is particularly pronounced for doctors, possibly because their observed adherence is relatively low when alone. Also, observed adherence in the presence of a critical care coworker is, in general, greater than in the presence of a nurse or a doctor. These differences are not statistically significant, and some of these results are associated with wide 95% CIs, because they are based on few observations.

Controlling for Confounding Factors

As discussed above, associations between the social variables and adherence might be explained by confounding factors rather than peer effects, so we performed tests to explore this possibility (Table 3). We see that increases in observed adherence are always associated with increases in the social variables, even when controlling for confounding factors. For example, the typical worker who has practiced hand hygiene at entry to a patient room encounters 0.2 more coworkers within the minute centered on the room entry time. This increase (like all other reported increases in this table) has a statistical significance less than .001. Table 3 shows results for event-detection parameter settings that lead to an optimal fit with respect to the night data and also illustrates these results under 2 other parameter settings. The results are consistent across all settings.

DISCUSSION

Our results demonstrate that the presence and proximity of other HCWs is associated with higher hand hygiene rates. Although the effect that we estimated was modest, the positive effect was consistent at different times of day, for different measures of social context, and after controlling for possible confounding factors. Furthermore, our results also indicate that rates increase as the social environment becomes more crowded, with diminishing marginal returns.

Other studies have described and speculated on the reasons for the presence of peer-like effects for hand hygiene.[17,18]

TABLE 3. Statistical Significance of the Influence of the Social Variables on Adherence, Controlling by Confounding Factor, for Different Event Detection Settings

Social variable, controlled confounder	Average difference	N	P
Fit to night data			
W1M			
Worker	0.191	259	<.001
Hospital room	0.209	337	<.001
No control	0.199	47,703	
SRSSI			
Worker	3.740	260	<.001
Hospital room	5.700	337	<.001
No control	−1.279	47,703	
Fit to day and night data			
W1M			
Worker	0.191	256	<.001
Hospital room	0.217	337	<.001
No control	0.191	47,694	
SRSSI			
Worker	3.618	257	<.001
Hospital room	6.082	337	<.001
No control	−1.519	47,694	
Strict identification of hand hygiene opportunities and dispenser activation[a]			
W1M			
Worker	0.251	227	<.001
Hospital room	0.455	294	<.001
No control	0.305	21,206	
SRSSI			
Worker	5.125	232	<.001
Hospital room	11.718	297	<.001
No control	1.927	21,206	

NOTE. Opportunities and dispenser activations are detected differently under different settings. Each row reports the average increase of the social variable upon adherence (average difference column), the number of pairs after matching by confounder (N), and the statistical significance of the increase assessed using Wilcoxon matched-pairs signed-rank test (P value). For reference, the noncontrolled average differences have been added as well; in such cases, the total number of opportunities, rather than the number of pairs, is given. The P value was not reported if insignificant (2-tailed t test, $P > .1$). SRSSI, sum of received signal strength to peers at the moment of the opportunity; W1M, the number of encounters within 1 minute of the opportunity.

[a] See Monsalve et al.[23]

However, these studies are relatively small in size and were primarily based on human observations. This is an important aspect to consider, given that the presence of human observers to monitor adherence have been reported to have a positive impact on hand hygiene.[13] Because of the reliance on human observers, these investigations were unable to capture fine-grained contact patterns at all hours of the day across an entire unit. Our approach allowed us to measure contacts throughout the entire unit, not just an observer's field of view.

Interestingly, our overall estimates of adherence rates were relatively low. Although not reported in our results section, human observers sporadically audited hand hygiene rates as part of standard practice, reporting rates greater than 50%. The rates measured by our automated system likely represent an underestimate, given that we did not count dispensing events inside patients' rooms that human observers might have identified. However, we believe our automated results were more representative, given the limited sampling by the human observers. Also, the error rates of human observers increase with busyness and distance,[30] and other studies of electronic monitoring systems have discovered similarly low rates.[31-34]

Our results are most informative for nurses, because they greatly outnumber the physicians and critical care personnel in our study. However, the results for doctors, showing that they had slightly lower observed adherence, are consistent with other reports in the literature.[35] Even though physicians seem to respond to social pressure more than do other HCWs, their observed adherence does not rise to the level of adherence of the other 2 job types. These findings suggest that peer effects may be tied to job types and worker culture. We did observe that critical support staff had more of an effect than other job types, perhaps because the presence of support staff may be a marker for more intensive social pressure, in excess of that measured by our SRSSI and W1M scores (eg, when multidisciplinary teams are rounding).

We were not able to detect individual workers who are able to inspire hand hygiene adherence in others. To preserve anonymity, we redistributed badges randomly after each shift. Had we been able to follow individuals over time, it is possible that individual-level peer effects may have emerged. This topic should be the focus of future investigations. The ability to discover authority and leadership effects from contact or social networks is an important objective and may have a broad range of implications beyond hand hygiene into other aspects of healthcare delivery and quality. Nevertheless, our random strategy appeared to be effective: with a very large staff, only 1 person refused to wear the badge, minimizing any potential bias from self-selection.

Finally, we observed differences in the social variables between day and night shifts. This probably occurred because instances when SRSSI values were higher (eg, more people were closer together) occurred less frequently at night. In addition, the interactions between HCWs and patients may be different in nature at night (eg, patients might be sleeping).

Our work is subject to a number of limitations. First, we defined hand hygiene opportunities as in-and-out-of-room rather than according to the World Health Organization's 5 moments.[36] Furthermore, we restricted our analysis to the dispensing events that occurred directly outside the patient room doors and ignored events that may have occurred inside rooms. We think that this is a defensible definition of a hand hygiene opportunity, because this is what the unit under study uses to measure adherence, and the HCWs are clearly expected to "rub in" and "rub out" for every room entry and exit. However, this definition could, in part, explain the low rates we observed.

Our second limitation is that, although we had badges for all HCWs in the unit, we did not give badges to consulting teams that periodically visit patients in the intensive care unit. Third, we did not instrument family members. Nevertheless, the MICU is a closed unit, and we were able to instrument the nurses and other HCWs who work exclusively on that unit. Fourth, we do not control for clustering of HCWs. However, we did control for worker type, which to some extent addresses the differences between HCWs that might arise due to differences in clustering. Finally, our study focuses on a single unit in a particular institution, and it is unclear whether the findings can be generalized to other healthcare settings.

Despite these limitations, we demonstrate a social effect on hand hygiene practice. Our results speak to the importance of the social environment in healthcare. In future studies, the ability to track HCWs across multiple shifts may help discover "super-influential" agents. The study of positive outliers may help us discover novel approaches to improve hand hygiene adherence and may also have implications for other behaviors related to patient safety. Finally, our results may have implications for disease modeling, a field that is increasingly stressing the importance of human behavior on the spread of diseases.

ACKNOWLEDGMENTS

Financial support. This work was supported in part from a cooperative agreement from the Centers for Disease Control and Prevention and the National Institutes of Health (research grant K01 AI75089). This work was also supported in part by the Iowa City Veterans Affairs Medical Research Foundation and the University of Iowa Health Care's eHealth and eNovation Center.

Potential conflicts of interest. All authors report no conflicts of interest relevant to this article. All authors submitted the ICMJE Form for Disclosure of Potential Conflicts of Interest, and the conflicts that the editors consider relevant to this article are disclosed here.

Address correspondence to Philip M. Polgreen, MD, MPH, Carver College of Medicine, Department of Internal Medicine, University of Iowa, Iowa City, IA 52242 (philip-polgreen@uiowa.edu).

REFERENCES

1. Boyce JM, Pittet D. Guidelines for hand hygiene in health-care settings: recommendations of the healthcare infection control practices advisory committee and the HICPAC/SHEA/APIC/IDSA hand hygiene task force. *Infect Control Hosp Epidemiol* 2002;23:S3–S41.
2. Erasmus V, Daha TJ, Brug H, et al. Systematic review of studies on compliance with hand hygiene guidelines in hospital care. *Infect Control Hosp Epidemiol* 2010;31(3):283–294.
3. Pittet D. Improving adherence to hand hygiene practice: a multidisciplinary approach. *Emerg Infect Dis* 2001;7:234–240.
4. Pittet D, Simon A, Hugonnet S, Pessoa-Silva CL, Sauvan V, Perneger TV. Hand hygiene among physicians: performance, beliefs, and perceptions. *Ann Intern Med* 2004;141(1):1–8.
5. Bischoff WE, Reynolds TM, Sessler CN, Edmond MB, Wenzel RP. Handwashing compliance by health care workers: the impact of introducing an accessible, alcohol-based hand antiseptic. *Arch Intern Med* 2000;160(7):1017–1021.
6. Kaplan LM, McGuckin M. Increasing handwashing compliance with more accessible sinks. *Infect Control* 1986;7:408–410.
7. Pittet D, Mourouga P, Perneger TV, et al. Compliance with handwashing in a teaching hospital. *Ann Intern Med* 1999;130:126–130.
8. Bittner MJ, Rich EC, Turner PD, Arnold WH Jr. Limited impact of sustained simple feedback based on soap and paper towel consumption on the frequency of hand washing in an adult intensive care unit. *Infect Control Hosp Epidemiol* 2002;23:120–126.
9. Pittet D. Promotion of hand hygiene: magic, hype, or scientific challenge? *Infect Control Hosp Epidemiol* 2002;23:118–119.
10. Rosenthal VD, McCormick RD, Guzman S, Villamayor C, Ore-

llano PW. Effect of education and performance feedback on handwashing: the benefit of administrative support in Argentinean hospitals. *Am J Infect Control* 2003;31(2):85–92.

11. Talbot TR, Johnson JG, Fergus C, et al. Sustained improvement in hand hygiene adherence: utilizing shared accountability and financial incentives. *Infect Control Hosp Epidemiol* 2013;34(11): 1129–1136.
12. Pittet D, Hugonnet S, Harbarth S, et al. Effectiveness of a hospital-wide programme to improve compliance with hand hygiene. Infection Control Programme. *Lancet* 2000;356(9238): 1307–1312.
13. Kohli E, Ptak J, Smith R, Taylor E, Talbot EA, Kirkland KB. Variability in the Hawthorne effect with regard to hand hygiene performance in high- and low-performing inpatient care units. *Infect Control Hosp Epidemiol* 2009;30(3):222–225
14. Eckmanns T, Besser J, Behnke M, Gastmeier P, Rüden H. Compliance with antiseptic hand rub use in intensive care units: the Hawthorne effect. *Infect Control Hosp Epidemiol* 2006;27:931–934.
15. Maury E, Moussa N, Lakermi C, Barbut F, Offenstadt G. Compliance of health care workers to hand hygiene: awareness of being observed is important. *Intensive Care Med* 2006;32(12): 2088–2089.
16. Chen LF, Carriker C, Staheli R, et al. Observing and improving hand hygiene compliance: implementation and refinement of an electronic-assisted direct-observer hand hygiene audit program. *Infect Control Hosp Epidemiol* 2013;34(2):207–210.
17. Lankford MG, Zembower TR, Trick WE, Hacek DM, Noskin GA, Peterson LR. Influence of role models and hospital design on hand hygiene of healthcare workers. *Emerg Infect Dis* 2003; 9(2):217–223.
18. Haessler S, Bhagavan A, Kleppel R, Hinchey K, Visintainer P. Getting doctors to clean their hands: lead the followers. *BMJ Qual Saf* 2012;21(6):499–502.
19. Christakis NA, Fowler JH. The collective dynamics of smoking in a large social network. *N Engl J Med* 2008;358(21):2249–2258.
20. Christakis NA, Fowler JH. The spread of obesity in a large social network over 32 years. *N Engl J Med* 2007;357(4):370–379.
21. Mas A, Moretti E. Peers at work. *Am Econ Rev* 2009;(1):112–145.
22. Monsalve M, Herman T, Pemmaraju S, Polgreen PM, Segre AM, Thomas G. Inferring realistic intra-hospital contact networks using link prediction and computer logins. In: Proceedings of the 2012 International Conference on Privacy, Security, Risk and Trust (PASSAT) and 2012 International Conference on Social Computing (SocialCom); September 3–5, 2012; Amsterdam, The Netherlands. IEEE 2012.
23. Monsalve M, Pemmaraju S, Polgreen PM. Interactions in an intensive care unit: experiences pre-processing sensor network data. In: Program and abstracts of the 4th Annual Wireless Health Conference; November 1–3, 2013; Baltimore, MD.
24. Polgreen PM, Hlady CS, Severson MA, Segre AM, Herman T. Method for automated monitoring of hand hygiene adherence without radio-frequency identification. *Infect Control Hosp Epidemiol* 2010;31(12):1294–1297.
25. Fries J, Segre AM, Thomas G, Herman T, Ellingson K, Polgreen PM. Monitoring hand hygiene via human observers: how should we be sampling? *Infect Control Hosp Epidemiol* 2012;33(7):689–695.
26. Hornbeck T, Naylor D, Segre AM, Thomas G, Herman T, Polgreen PM. Using sensor networks to study the effect of peripatetic healthcare workers on the spread of hospital-associated infections. *J Infect Dis* 2012;206(10):1549–1557.
27. Vanhems P, Barrat A, Cattuto C, et al. Estimating potential infection transmission routes in hospital wards using wearable proximity sensors. *PLoS One* 2013;11;8(9):e73970.
28. Friggeri A, Chelius G, Fleury E, Fraboulet A, Mentré F, Lucet JC. Reconstructing social interactions using an unreliable wireless sensor network. *Comput Commun* 2010;33(12):609–618.
29. Galbraith S, Daniel JA, Vissel B. A study of clustered data and approaches to its analysis. *J Neurosci* 2010;30(32):10601–10608.
30. Sharma D, Thomas GW, Foster ED, et al. The precision of human-generated hand hygiene observations: a comparison of human observation with an automated monitoring system. *Infect Control Hosp Epidemiol* 2012;33(12):1259–1261.
31. Swoboda SM, Earsing K, Strauss K, Lane S, Lipsett PA. Electronic monitoring and voice prompts improve hand hygiene and decrease nosocomial infections in an intermediate care unit. *Crit Care Med* 2004;32:358–363.
32. Cheng VC, Tai JWM, Ho SKY, et al. Introduction of an electronic monitoring system for monitoring compliance with moments 1 and 4 of the WHO "my 5 moments for hand hygiene" methodology. *BMC Infect Dis* 2011;11:1–13.
33. Swoboda SM, Earsing K, Strauss K, Lane S, Lipsett PA. Isolation status and voice prompts improve hand hygiene. *Am J Infect Control* 2007;32:358–363.
34. Fisher DA, Seetoh T, Oh May-Lin H, et al. Automated measures of hand hygiene compliance among healthcare workers using ultrasound: validation and a randomized controlled trial. *Infect Control Hosp Epidemiol* 2013;34(9):919–928.
35. Duggan JM, Hensley S, Khuder S, Papadimos TJ, Jacobs L. Inverse correlation between level of professional education and rate of handwashing compliance in a teaching hospital. *Infect Control Hosp Epidemiol* 2008;29(6):534–538.
36. Sax H, Allegranzi B, Chraïti MN, Boyce J, Larson E, Pittet D. The World Health Organization hand hygiene observation method. *Am J Infect Control* 2009;37:827–834.