Connecting pathogen transmission and healthcare worker cognition: a cognitive task analysis of infection prevention and control practices during simulated patient care

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ABSTRACT

Background  Relatively little is known about the cognitive processes of healthcare workers that mediate between performance-shaping factors (eg, workload, time pressure) and adherence to infection prevention and control (IPC) practices.  We taxonomised the cognitive work involved in IPC practices and assessed its role in how pathogens spread.

Methods  Forty-two registered nurses performed patient care tasks in a standardised high-fidelity simulation.  Afterwards, participants watched a video of their simulation and described what they were thinking, which we analysed to obtain frequencies of macrocognitive functions (MCFs) in the context of different IPC practices.  Performance in the simulation was the frequency at which participants spread harmless surrogates for pathogens (bacteriophages).  Using a tertiary split, participants were categorised into a performance group: high, medium or low.  To identify associations between the three variables—performance groups, MCFs and IPC practices—we used multiblock discriminant correspondence analysis (MUDICA).

Results  MUDICA extracted two factors discriminating between performance groups.  Factor 1 captured differences between high and medium performers.  High performers monitored the situation for contamination events and mitigated risks by applying formal and informal rules or managing their uncertainty, particularly for sterile technique and cleaning.  Medium performers engaged more in future-oriented cognition, anticipating contamination events and planning their workflow, across many IPC practices.  Factor 2 distinguished the low performers from the medium and high performers who mitigated risks with informal rules and sacrificed IPC practices when managing tradeoffs, all in the context of minimising cross-contamination from physical touch.

Conclusions  To reduce pathogen transmission, new approaches to training IPC (eg, cognitive skills training) and system design are needed.  Interventions should help nurses apply their knowledge of IPC fluidly during patient care, prioritising and monitoring situations for risks and deciding how to mitigate risks.  Planning IPC into one’s workflow is beneficial but may not account for the unpredictability of patient care.

WHAT IS ALREADY KNOWN ON THIS TOPIC

Factors internal and external to healthcare workers affect adherence to infection prevention and control practices.

WHAT THIS STUDY ADDS

We described the cognitive work of practising infection prevention and control, which transforms these factors into behaviours.

We then identified the forms of cognitive work that were associated with the spread of surrogate pathogens during simulated patient care.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

The current research can be used to better support healthcare workers practising infection prevention and control by redesigning healthcare systems as well as developing a cognitive skills training to improve macrocognition, such as monitoring and decision making.

INTRODUCTION

Healthcare-associated infections affect approximately 1 in 31 hospitalised patients, leading to 90,000 deaths...
annually in the USA alone and placing a significant financial burden on healthcare systems.\(^2\) Common infection prevention and control (IPC) practices, such as hand hygiene or using personal protective equipment (PPE), could prevent up to 70% of these infections if applied effectively by healthcare workers (HCWs).\(^3\) As breaches in IPC practices are common,\(^1\)\(^3\) attention has been devoted to identifying factors, both internal and external to HCWs, that influence adherence to IPC. Internal factors include HCWs’ knowledge,\(^6\)\(^7\) perceptions\(^6\)\(^7\) and attitudes towards IPC practices.\(^6\)\(^7\) External factors include system characteristics, such as the design of the built environment,\(^6\) tasks,\(^6\)\(^8\) supplies or equipment\(^5\) and the organisation.\(^6\)

Relatively less is known about the cognitive processes of HCWs that transform these factors into behaviours.\(^9\)\(^10\) For example, decision making in complex settings like healthcare often involves making tradeoffs between competing priorities, which are compelled by external factors (eg, time pressure) and resolved, in part, by internal factors (eg, perceptions of risk) to produce behaviour (eg, not performing hand hygiene). Describing these processes, or the cognitive work involved in applying IPC practices, is useful for improving adherence to IPC practices as it may help explain both positive and negative HCW behaviours. Understanding how HCWs integrate IPC into the complexities of patient care could identify forms of cognitive work that should be supported through better system design\(^6\)\(^11\) or strengthened with training.\(^11\)\(^12\)

In the present study, we described the cognitive work of IPC in terms of macrocognition, which refers to the high-level cognitive processes by which people manage complex situations.\(^10\)\(^11\) Macrocognition identifies several key functions,\(^11\)\(^13\)\(^14\) which include decision making,\(^13\)\(^15\) planning,\(^13\)\(^14\) sensemaking\(^14\) and monitoring.\(^13\)\(^14\) Because macrocognition is a generic framework, however, we sought to first describe these macrocognitive functions (MCFs) in the context of IPC. Second, we sought to understand how these forms of cognitive work relate to the spread of pathogens during simulated patient care.

**METHODS**

As the goal of IPC is to prevent the spread of pathogens, we measured HCW performance in terms of the frequency at which they spread surrogate pathogens to surfaces in a challenging high-fidelity simulation. To connect performance with cognitive processes, we performed a cognitive task analysis, which is a systematic process for capturing and eliciting the cognitive processes underlying task performance.\(^11\) We elicited these processes by asking HCWs to report their thoughts while watching a video recording of their simulation (ie, a think-aloud) to avoid interfering with task performance.\(^11\)

**Participants**

As nurses comprise the largest group of HCWs and have frequent contact with patients, we recruited 45 registered nurses from a tertiary/quaternary academic medical centre, using flyers and unit announcements. Inclusion criteria were being at least 18 years of age and working as a registered nurse in an emergency department, intensive care unit or medical/surgical unit. We excluded two participants because of equipment issues, and one participant was excluded for not completing the simulation. The remaining 42 participants (median=4.89 years since first licensure, IQR 2.32–18.23) came from the intensive care unit (n=13), emergency department (n=12) and medical/surgical unit (n=17). For 2.5 hours, participants were compensated with US$125.

**Simulation design**

Simulations were conducted at Emory University School of Medicine’s simulation centre. We developed a standardised simulation scenario involving two male adult inpatients (Laerdal SimMan high-fidelity patient manikins), in separate rooms, who required only standard precautions (see online supplemental material for patient descriptions and simulation layout). Based on prior research,\(^16\) we selected tasks that were high or low in the perceived risk of infection to the patient and high or low in the perceived risk of HCW contamination.\(^17\) Patient 1’s tasks were changing the dressing on a stage 4 sacral pressure injury, toileting with a bedpan, inserting a nasogastric tube and inserting a peripheral intravenous line (PIV). Patient 2’s tasks were inserting an indwelling urinary catheter, collecting a stool specimen, auscultating heart and breath sounds and administering an intravenous medication. Manikins could converse with participants but could not move themselves.

Tasks were documented in a simulated electronic medical record that was accessed from a mobile workstation-on-wheels. Additionally, simulations contained common challenges to applying IPC practices\(^5\)\(^18\): participants did not receive assistance from other staff (short-staffed), were instructed they had 1 hour to complete and document tasks (time-pressure) and were interrupted twice in each patient room at specific moments during tasks (see online supplemental material for details). PPE and products for cleaning patients and environmental disinfection were available in the patient’s supply cart. Alcohol-based hand rub dispensers were located on entry and exit of patient rooms.

**Procedure**

Before simulations, four variants of bacteriophage \(\lambda\) were applied to unique target sites\(^19\): \(\lambda^{\text{Temp}}\) on patient 1’s stage 4 pressure injury, \(\lambda^{\text{Kan}}\) on patient 1’s stool in a bedpan beneath the patient, \(\lambda^{\text{Chl}}\) on patient 2’s genitalia and \(\lambda^{\text{Vir}}\) on patient 2’s stool on a disposable underpad.
beneath the patient. Two of the four tasks for each patient harboured a different source of contamination: changing the dressing on pressure injury (λ.Temp), toileting in bed (λ.KaP), inserting a Foley catheter (λ.Chl) and collecting a stool specimen (λ.Vi).

Before the start of the simulation, a researcher consented participants and collected demographic data, such as experience and area of practice. Participants understood that there may be contamination in each room but were unaware of its locations, sampling sites and that we were only interested in IPC. Participants donned a pair of disposable scrubs, and the researcher then oriented them to the simulation space, equipment and supplies, high-fidelity manikins and tasks by walking through the supply room, two patient rooms and hallway between them. To minimise observation effects, we explained that the simulation was an opportunity to learn how to improve clinical practices based on the aggregate performance of participants. A researcher then placed a GoPro HERO8 mobile camera on the participant’s forehead outside of the patient rooms, after which a clinical-researcher gave a scripted handover for each patient at the bedside. Participants then performed the eight tasks in any order they wished. Although participants were told they had 1 hour to complete the simulation, we allowed participants to exceed 1 hour to complete all tasks.

After the simulation, participants performed a cued-retrospective think-aloud in a separate debriefing room, in which they described what they were thinking about in the simulation while watching a video playback from their point of view. The think-aloud and playback were recorded synchronously. While the participant performed the think-aloud, we sampled 16 sites from the simulation grouped into 4 types of surfaces: high-touch surfaces, workstation-on-wheels surfaces, nurse surfaces and patient critical sites. High-touch surfaces included the bedside table, bedrails, bedrail controls, vital signs monitor and supply cart in each patient room. Workstation-on-wheels surfaces included the keyboard and table. Nurse surfaces included the nurse’s bare hands and disposable scrubs. Patient critical sites included patient 1’s sacral pressure injury and patient 2’s genitalia. Each surface was sampled for the presence of each λ-variant. After sampling, surfaces were disinfected with 70% ethanol, DNA Away, RNase Away and Lysol wipes. Phage identification of positive surfaces samples was determined by direct PCR testing. Online supplemental figures S1 and S2 show a flow diagram of the procedure and layout of the simulation space, respectively.

Analysis

Measuring performance

For each of the four surface types—(1) high-touch surfaces, (2) surfaces on the workstation-on-wheels, (3) surfaces on the nurse and (4) patient critical sites—we calculated the percentage of surfaces that became contaminated with bacteriophage during the simulation. We then calculated an overall performance score that was a weighted average of the four surface types with weights reflecting the severity of contaminating each type of surface. We obtained weights using the Analytical Hierarchy Process, where subject matter experts, including two infection preventionists, two infectious disease physicians and two nurses from a biocontainment unit, rated in a pairwise fashion the relative importance of each surface type on a standard 9-point scale in contributing to the likelihood of a patient becoming colonised with a bacterial pathogen while in the hospital. Ratings were aggregated using the geometric mean, and weights were derived using the eigenvalue method in the abpsurvey package in R.

Contaminating patient critical sites had the greatest weight (50.49%), followed by self-contamination (26.09%), high-touch surfaces (14.88%) and surfaces on the workstation-on-wheels (8.54%).

Segmenting think-alouds

Think-alouds were transcribed into verbalisations, which were complete thoughts separated by a significant pause. Two nurses independently coded verbalisations for whether the participant was clearly thinking about IPC, which was defined as whether a verbalisation either described recognising a risk related to IPC or referred to an IPC practice. A third nurse resolved disagreements. Inter-rater reliability (IRR) was assessed with Gwet’s agreement coefficient 1 (AC1). IRR was nearly perfect (AC1 = 0.91).

Content analyses of think-alouds

Our goals were, first, to verify the involvement of MCFs in IPC practices and, second, to describe MCFs in the context of IPC. Thus, analyses of the think-alouds comprised two phases: a deductive content analysis, in which we categorised verbalisations in terms of MCFs, followed by an inductive content analysis, in which we identified and assigned verbalisations to subcategories of MCFs derived from the think-aloud data. Frequencies of subcategories were obtained for subsequent analysis. In the deductive content analysis, two human factors experts independently coded verbalisations for whether they involved each of the four MCFs (Table 1). IRR for each MCF was based on 14 randomly selected transcripts; the remaining transcripts were divided equally between the two coders. Final codes for dually coded transcripts came equally from both coders. In the inductive content analysis, verbalisations involving any MCF were written on separate cards and grouped according to MCF. To identify subcategories of each MCF, two human factors experts and three nurses independently performed open card sorts of verbalisations, where each sorter grouped
### Table 1: Macro-cognitive functions (MCFs)’ definitions, inter-rater reliability (IRR) and prevalence

<table>
<thead>
<tr>
<th>Categories and subcategories of MCFs</th>
<th>Definition</th>
<th>IRR</th>
<th>Percentage of verbalisations*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitoring</td>
<td>Tracking implementation progress to maintain situation awareness or discovering that a situation is deviating from its expected course.13 14</td>
<td>0.64&lt;sup&gt;c&lt;/sup&gt;</td>
<td>44%</td>
</tr>
<tr>
<td>Tracking adherence to IPC protocol</td>
<td>Actively thinking about when or how one should do things to prevent later infection in a patient or healthcare worker including the adequacy of an IPC protocol and detecting deviations from an IPC protocol.</td>
<td>0.30&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(62%)</td>
</tr>
<tr>
<td>Detecting problem of difficulty using PPE</td>
<td>Experiences trouble while using PPE.</td>
<td>0.96&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(8%)</td>
</tr>
<tr>
<td>Detecting a contamination event</td>
<td>Recognising that something, which is not normally contaminated, is no longer sterile or clean.</td>
<td>0.59&lt;sup&gt;d&lt;/sup&gt;</td>
<td>(26%)</td>
</tr>
<tr>
<td>Detecting problem of having limited resources</td>
<td>Recognising that resources are insufficient for the task at hand.</td>
<td>0.94&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(7%)</td>
</tr>
<tr>
<td>Detecting problem of lack of knowledge</td>
<td>Recognising that one does not know how to perform a procedure or whether to perform a procedure in a clean or in a sterile manner.</td>
<td>0.92&lt;sup&gt;d&lt;/sup&gt;</td>
<td>(3%)</td>
</tr>
<tr>
<td>Planning</td>
<td>‘Generating [or] adapting methods for action to transform current state into desired future state’ (Mickelson et al.,13 p. 7).</td>
<td>0.88&lt;sup&gt;d&lt;/sup&gt;</td>
<td>13%</td>
</tr>
<tr>
<td>Sequencing patients</td>
<td>Thinking about the order to care for patients.</td>
<td>0.95&lt;sup&gt;d&lt;/sup&gt;</td>
<td>(6%)</td>
</tr>
<tr>
<td>Sequencing tasks</td>
<td>Thinking about the order that tasks should be completed for a patient.</td>
<td>0.62&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(27%)</td>
</tr>
<tr>
<td>Sequencing steps in a task</td>
<td>Thinking about the order of steps or what steps to take to complete a task correctly and efficiently regardless of whether the participant has started a task.</td>
<td>0.55&lt;sup&gt;b&lt;/sup&gt;</td>
<td>(33%)</td>
</tr>
<tr>
<td>Preparing for task</td>
<td>Before starting a task, thinking about how or taking actions to set up for a task.</td>
<td>0.50&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(37%)</td>
</tr>
<tr>
<td>Sensemaking</td>
<td>‘A deliberate and systematic attempt to find a coherent, conceptual situational understanding [or] acquire new knowledge’ (Holtrop et al.,14 p. 2); this understanding can be used to explain previous events or anticipate future events.63</td>
<td>0.84&lt;sup&gt;d&lt;/sup&gt;</td>
<td>17%</td>
</tr>
<tr>
<td>Assessing what resources are available for applying IPC practices</td>
<td>Assessing what resources are available for applying IPC practices or where resources are located.</td>
<td>0.77&lt;sup&gt;d&lt;/sup&gt;</td>
<td>(32%)</td>
</tr>
<tr>
<td>Anticipating a contamination event in a situation</td>
<td>Foreseeing a contamination event that will, or could, occur in a situation. That is, anticipating that something, which is not normally contaminated, will or could become soiled or dirty.</td>
<td>0.59&lt;sup&gt;d&lt;/sup&gt;</td>
<td>(27%)</td>
</tr>
<tr>
<td>Identifying appropriate IPC practices in a situation</td>
<td>Identifying the proper action to take or how to perform that action in a situation, from an IPC perspective.</td>
<td>0.43&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(34%)</td>
</tr>
<tr>
<td>Assessing whether a surface is sterile, clean or dirty</td>
<td>Determining whether a surface is sterile, clean or dirty. This does not include detecting a contamination event or actively tracking whether a surface is currently sterile, clean or dirty.</td>
<td>0.86&lt;sup&gt;d&lt;/sup&gt;</td>
<td>(8%)</td>
</tr>
<tr>
<td>Decision making</td>
<td>The cognitive process of choosing and committing to one or more options or courses of actions.13 15</td>
<td>0.59&lt;sup&gt;d&lt;/sup&gt;</td>
<td>49%</td>
</tr>
<tr>
<td>Try to reduce or resolve uncertainty</td>
<td>When deciding what to do under uncertainty, try to lessen one’s uncertainty by collecting additional information or thinking through an approach.</td>
<td>0.71&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(13%)</td>
</tr>
<tr>
<td>Accept uncertainty but proceed cautiously</td>
<td>When deciding what to do under uncertainty, one assumes the worst-case scenario is true and acts accordingly, instead of trying to lessen uncertainty.</td>
<td>0.68&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(13%)</td>
</tr>
<tr>
<td>Follow a formal rule</td>
<td>When deciding what rule to follow in a situation, following a rule that is based on protocol, policy or best-practice.</td>
<td>0.67&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(29%)</td>
</tr>
<tr>
<td>Follow an informal rule</td>
<td>When deciding what rule to follow in a situation, following a rule that deviates from a formal rule and is instead based on personal preferences, attitudes, experience or social norms.</td>
<td>0.73&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(12%)</td>
</tr>
<tr>
<td>Compromise on the quality of an IPC practice</td>
<td>When deciding how to balance IPC with other constraints or priorities, finding a solution that is workable but less than ideal, from an IPC perspective.</td>
<td>0.72&lt;sup&gt;c&lt;/sup&gt;</td>
<td>(13%)</td>
</tr>
</tbody>
</table>

Continued
similar verbalisations together and described their groupings. Sorters then discussed their groupings to arrive at a consensual set of subcategories and their definitions. To measure IRR, and obtain frequencies of these subcategories, five nurses (two of whom did not develop the coding scheme) performed closed card sorts,35 where verbalisations were sorted into the subcategories. The final assignment of a verbalisation to a subcategory reflected the simple majority of the five sorters’ judgements for a verbalisation. Open and closed card sorts were performed with the Proven By Users online card-sorting tool.37

Lastly, verbalisations involving any MCF subcategory were coded for the IPC practices they involved: hand hygiene; cleaning the patient, environment or equipment; achieving or maintaining sterility; PPE; disposing or containing potentially contaminated material; or minimising contamination via contact (see online supplemental material Table S1 for definitions). One human factors expert and one nurse independently performed a closed card sort of verbalisations (see ‘IPC practices’ section for agreement statistics). The final assignment of a verbalisation to an IPC practice(s) reflected the agreement of the two coders; a second human factors expert resolved disagreements.

### Multiblock discriminant correspondence analysis

To identify associations between performance groups, MCFs subcategories and IPC practices, we used multiblock discriminant correspondence analysis (MUDICA).38 39 MUDICA is a multivariate statistical technique for identifying variables that are important for discriminating between groups of individuals. MUDICA is non-parametric and is appropriate when the number of variables exceeds the number of observations.39

In MUDICA, the extent to which the co-occurrences of groups and variables deviate from independence is akin to the total variance of the data,40 which MUDICA decomposes into a set of orthogonal factors along which groups and variables are represented as factor scores; the first factor explains the greatest amount of variance (its eigenvalue, $\lambda$), the second factor explains the greatest amount of residual variance and so forth. Each factor maximises between group differences, capturing important and unique associations between these groups and variables. We performed MUDICA using R.38 41

MUDICA analyses a group by variable contingency table, where groups were the three performance groups and variables were formed by crossing the 19 MCF subcategories (table 1) with the 6 IPC practices. Variables contained the frequencies at which each MCF subcategory occurred in the context of each IPC practice for each performance group. After removing variables occurring less than twice, 83 variables remained for analysis. MUDICA analyses the contributions of groups and variables, and the contributions of blocks of related variables, which collectively offer more information than individual variables.38 39 Blocks were the 19 MCF subcategories. To ensure that the contribution of a block was unrelated to the number of variables comprising it (median=5 variables; range=1–6), we used a normalisation procedure in which the frequencies in a block were divided by the number of variables in that block prior to analysis (Krishnan, personal communication).

### RESULTS

#### HCW performance

Of all contaminated sampling sites, high-touch surfaces were most common (47%), followed by surfaces on the nurse (26%), patient critical sites (16%) and the workstation-on-wheels (11%). Overall performance scores ranged from 38% to 100% (M=77%, SD=15.3%), with higher scores indicating better performance (figure 1). We ranked ordered participants according to their overall performance score and categorised them into high (n=13), medium (n=16) or low (n=13) performers using a tertiary split. Group size varied slightly due to ties. For most surface types, the average percentage of contaminated sampling sites per participant was lowest for the highest performers: contaminating a critical site on a patient (high performers=0%, medium=22%, low=42%), self-contamination (high=19%, medium=31%,

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**Table 1 Continued**

<table>
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<th>Definition</th>
<th>IRR</th>
<th>Percentage of verbalisations*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sacrifice an IPC practice</td>
<td>When deciding how to balance IPC with other constraints or priorities, recognising the relevance of an IPC practice in a situation, but deciding against performing that practice entirely because of constraints or greater priorities</td>
<td>0.82²</td>
<td>(12%)</td>
</tr>
</tbody>
</table>

Note: a=fair agreement; b=moderate agreement; c=substantial agreement; d=almost perfect agreement.33

*Percentages without parentheses are the percentage of all relevant verbalisations that were coded as the MCF in that row. Percentages with parentheses are the percentage of verbalisations that were coded as the subcategory for that row out of the number of verbalisations for that given MCF. As verbalisations could be coded into multiple MCF categories or subcategories, percentages may sum to >100%. Not shown is an ‘other’ subcategory for each MCF (1% of monitoring verbalisations were coded as ‘other’, 0% for planning, 6% for sensemaking, 1% for decision making) and uncategorised verbalisations (0.4% of monitoring verbalisations were not categorised, 1% for planning, 0% for sensemaking, 10% for decision making).

IPC, infection prevention and control; PPE, personal protective equipment.
low=58%) and the workstation-on-wheels (high=4%, medium=9%, low=31%). Contaminating a high-touch surface, however, was similar between groups (high=11%, medium=14%, low=14%). Overall performance was not significantly associated with experience (ie, years since licensure; \( r_s = 0.07, p = 0.64 \)), unit type (\( F = 0.89, p = 0.42, \eta^2_p = 0.04 \)) nor time to complete the simulation (one participant removed due to technical difficulties; \( M = 65 \text{ min}, \sigma = 8, r_s = 0.16, p = 0.33 \)).

**Content analyses of think-alouds**

In the deductive content analysis, IRR of coding MCFs ranged from moderate to nearly perfect (AC1 range=0.59–0.88, median=0.74; table 1). From a total of 973 verbalisations, 598 (61%) described at least one MCF; the remaining verbalisations did not reflect participants’ thinking during the simulation (eg, comments based on hindsight or digressions). Of the 598 verbalisations, 49% described decision making, 44% monitoring, 17% sensemaking and 13% planning. Across the four MCFs, inductive content analysis produced 19 subcategories of MCFs, with IRR ranging from fair to nearly perfect (AC1 range=0.30–0.96, median=0.71; table 1). Table 1 shows percentage of verbalisations categorised into MCF subcategories. For each MCF, nearly all verbalisations involved at least one subcategory of that MCF (verbalisations could be categorised as ‘other’; see table 1 note): monitoring=99% of verbalisations, planning=99%, sensemaking=94% and decision making=90%.

**IPC practices**

IRR of coding IPC practices (see online supplemental material for definitions) ranged from substantial to nearly perfect: minimising contamination from contact (AC1=0.62; 16% of verbalisations); cleaning the patient, equipment or environment (AC1=0.85; 18%); disposing or containing potentially contaminated material (AC1=0.89; 33%); achieving or maintaining sterility (AC1=0.89; 19%) and hand hygiene (AC1=0.95; 7%). Ninety-five per cent of MCF subcategories occurred (at least twice) in the context of achieving or maintaining sterility, 84% minimising contamination from contact (‘contact contamination’), 79% cleaning the patient, equipment or environment, 79% using

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![Figure 1](http://qualitysafety.bmj.com/)

**Figure 1** The overall performance score for each nurse is shown in green. The other coloured bars reflect the weighted percentage of contaminated sampling sites for each surface type, which detract from one’s overall performance score. ED, emergency department; ICU, intensive care unit; MS, medical/surgical; WoW, workstation-on-wheels.
PPE, 58% disposing or containing potentially contaminated material and 42% hand hygiene.

**Multiblock discriminant correspondence analysis**

MUDICA extracted two factors, which explained 52.1% ($\lambda=0.15$) and 47.9% ($\lambda=0.14$) of the variance in the contingency table, respectively. A permutation test with 10,000 permutations\(^3\) showed that a significant proportion of the variance was driven by differences between performance groups, $R^2=0.66$ ($p_{	ext{perm}}<0.001$); all groups differed significantly from one another in the factor space (figure 2) as indicated by non-overlapping 95% confidence ellipses based on 1000 bootstrapped resamples.\(^3\) We interpret each factor based on the groups, blocks and the variables comprising the blocks that occupy the positive or negative side of a factor and contribute substantially to the variance of that factor (see figures 3 and 4). A substantial contribution is one that is larger than the average contribution (ie, 1 divided by the number of elements\(^3\)): $\frac{1}{3}$ (33.33%) for groups, $\frac{1}{17}$ (5.26%) for blocks and $\frac{1}{8}$ (1.20%) for variables.

Factor 1 reflected differences between the high and medium performance groups (figure 3A). Contrary to medium performers, high performers were distinguished by how they monitored and made decisions during patient care (figure 3B), primarily in the context of achieving or maintaining sterility and when cleaning the patient, environment or equipment (figure 3C). Specifically, high performers were more often recognising risks as situations unfolded, such as detecting contamination events during sterile technique. When deciding how to mitigate risks, high performers more often applied both formal rules (eg, cleaning stethoscope before use, cleaning PIV catheter hub before medication administration) as well as informal rules (eg, putting an extra underpad beneath patient during wound care to facilitate cleaning, bringing an extra pair of sterile gloves for Foley catheter insertion). Lastly, high performers were more often aware of a lack of knowledge, and when unable to resolve their uncertainty about what to do, they devised a cautious approach (eg, treating wound care as a sterile procedure when uncertain, avoiding using a potentially contaminated bedside table for PIV insertion because of insufficient time to clean).

Contrary to high performers, medium performers were distinguished by how they engaged more in forms...
Figure 3  Important signed contributions to factor 1 from groups, blocks and variables. Contributions are the percentage of the variance of a factor accounted for by a given group, block or variable. The sign of a contribution indicates whether an element contributes to the positive or negative side of a factor. Dashed lines indicate the threshold for a substantial contribution; subthreshold blocks and variables not shown. The colours of variables in C correspond to the colours of the blocks in B to which they belong; grey bars in C indicate variables that did not belong to a block in B. IPC, infection prevention and control; PPE, personal protective equipment.
Figure 4  Important signed contributions to factor 2 from groups, blocks and variables. Contributions are the percentage of the variance of a factor accounted for by a given group, block or variable. The sign of a contribution indicates whether an element contributes to the positive or negative side of a factor. Dashed lines indicate the threshold for a substantial contribution; subthreshold blocks and variables not shown. The colours of variables in C correspond to the colours of the blocks in B to which they belong; gray bars in C indicate variables that did not belong to a block in B. IPC, infection prevention and control; PPE, personal protective equipment.
of future-oriented cognition: anticipating contamination events (eg, pre-emptively double-gloving for tasks involving bodily fluids) and preparing for tasks (eg, placing Foley catheter insertion kit where it will not become contaminated during procedure), planning the sequence of tasks (eg, performing clean before dirty tasks) and planning the sequence of steps of tasks (eg, mentally reviewing the steps for inserting a Foley catheter; figure 3B). Medium performers engaged in these forms of sensemaking and planning across a variety of IPC practices, including achieving or maintaining sterility, minimising contamination by contact and using PPE (figure 3C).

Factor 2 reflects associations that distinguish the low performers from the medium and high performers (figure 4A). Low performers were characterised by how they monitored and responded to the ongoing situation (figure 4B), all of which was done in the context of minimising contamination via contact (figure 4C). Specifically, low performers were more often tracking what they touched and detecting contamination events. They mitigated risks by more often applying informal rules (eg, avoiding touching objects after touching patients) and deciding to sacrifice IPC practices when constraints or competing priorities arose (eg, not cleaning a bedside table because of fatigue, not cleaning the PIV insertion site because of time pressure). Moreover, low performers were also characterised by how they neglected to assess certain aspects of situations (ie, whether a surface is sterile, clean or dirty and identifying appropriate IPC practices in a situation) as well as manage their uncertainty (ie, proceed cautiously when uncertain; figure 4B), either in the context of achieving or maintaining sterility or using PPE (figure 4B).

DISCUSSION

Healthcare-associated infections have devastating effects yet are largely preventable with common IPC practices. In the present study, we measured how successfully HCWs prevented the spread of surrogate pathogens to surfaces during simulated patient care. Contamination spread in simulation resembled that during actual patient care, with high- and low-performing HCWs successfully HCWs prevented the spread of surrogate pathogens to surfaces during simulated patient care. However, low performers primarily monitored and responded to situations to avoid spreading contamination by physical touch (cf. high performers’ focus on sterile technique and cleaning). Minimising contamination from contact depends on accurately assessing whether a surface is contaminated. However, low performers notably under-reported assessing whether surfaces were sterile, clean or dirty. Moreover, physical contact with the patient and their environment often occurs inadvertently, outside of the HCW’s awareness. The cognitive style of low performers seems to reflect a misguided belief system that deprioritises IPC (eg, sacrificing IPC practices) and holds that simply avoiding spreading contamination through touch and following informal rules will achieve acceptable performance.

Differences between performance groups suggest that tailored training approaches are needed; low performers appear to have a belief system that should...
thought processes, which does not capture aspects of our measures of cognition, participants described their person inserting the catheter and stop the procedure multiple HCWs; by having one person monitor the distributing the cognitive work of monitoring across participants who performed highly (or poorly) may have done so at the expense (or benefit) of other facets of performance, such as patient stability, patient satisfaction or efficiency. The present study taxonomised the cognitive work of performing common IPC practices and demonstrated that the forms of work in which one engages is associated with how pathogens disseminate during simulated patient care. Differences between performance groups suggest new targets and approaches for training HCWs in IPC as well as system design. Interventions should help nurses apply their knowledge of IPC fluidly during patient care (cf. high performers) by prioritising and monitoring situations for risks (eg, during sterile technique) and deciding how to mitigate risks with formal rules or principles. The benefits of taking a primarily proactive approach to practising IPC are limited as plans may need to be adapted or abandoned to account for the dynamics of patient care. Future research should confirm our results in different institutions and patient populations and investigate the origins of cognitive differences, particularly with respect to the role of internal factors (eg, HCW beliefs and types of experience).7

Complementary to training efforts, understanding the cognitive work of IPC can also inform interventions for allocating MCFs, such as monitoring, across people or technology during IPC practices.11 For example, high performers were focused on detecting breaches in their sterile technique and, simultaneously, did not contaminate the patient’s genitalia during Foley catheter insertion. Monitoring, therefore, appears to be an important form of cognitive work for achieving and maintaining sterility. In the context of sterile procedures such as central line or Foley catheter insertion, the use of two-person teams has reduced central line-associated bloodstream infections56 57 and catheter-associated urinary tract infection58 in part by distributing the cognitive work of monitoring across multiple HCWs; by having one person monitor the person inserting the catheter and stop the procedure if sterility is broken, some of the cognitive work of the person inserting the catheter is offloaded.

The present study has several limitations. Regarding our measures of cognition, participants described their thought processes, which does not capture aspects of cognition that occur outside one’s awareness, such as executing highly practiced behaviours.59 Even so, the think-aloud method is useful for capturing aspects of cognition that require effortful, conscious processing (eg, decision making),60–62 which aligns with our goal of identifying forms of cognitive work. Our performance measure is also limited; although the surfaces we contaminated or sampled were grounded in the literature,19 23–26 we could not exhaustively sample surfaces comprising each type of surface nor could we exhaustively contaminate surfaces given the limited number of bacteriophage λ variants.30 Additionally, participants who performed highly (or poorly) may have done so at the expense (or benefit) of other facets of performance, such as patient stability, patient satisfaction or efficiency.17

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Original research

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REFERENCES

27 Saaty RW. The analytic hierarchy process—what it is and how it is used. Mathematical Modelling 1987;9:161–76.
33 Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics* 1977;33:159.
57 Pronovost P, Vohr E. Safe patients, smart hospitals: how one doctor’s checklist can help us change health care from the inside out. Penguin, 2010: 201.
Supplemental Material

Procedure

In addition to the text describing the procedure in the main text, we provide a flow diagram of the procedure as shown in Figure S1.

Figure S1. Flow Diagram of Simulation Procedure

Patient Descriptions

For the simulations, we developed realistic descriptions and medical history for the high-fidelity manikins in the simulation; these descriptions were not based on or represent real patients. Patient 1 was a 67-year-old male and nursing home resident, with a past medical history of stroke. He presented with nausea and concern for ileus. He was allergic to Sulfa drugs. The off-going nurse’s assessment indicated he was hemodynamically stable, awake, and alert with some left-sided weakness. The wound care team...
had already seen him, and they left orders for his stage IV sacral decubitus ulcer. He had one peripheral IV with normal saline going, but he needed a second peripheral IV. There was concern for an ileus, prompting the need for a nasogastric tube. The off-going nurse had already put him on a bedpan.

Patient 2 was a 58-year-old male with stage 3 chronic kidney disease and paroxysmal Atrial Fibrillation. He presented with palpitations, lower abdominal pain, and diarrhea. He was allergic to Lisinopril and betadine. He had just come in and was awake and alert but complaining of urine and stool incontinence. He was hooked up to telemetry, which showed Atrial Fibrillation with rates in the 120s to 130s. Cardiology had assessed him and wasn’t too concerned. He was late for his dose of Metoprolol 5 mg IV. The off-going nurse had just checked his blood pressure, which was 130s/70s, but hadn’t done any other assessment. Ceftriaxone was ordered out of concern for a urinary tract infection, which was already hung and had another hour left. He already had one peripheral IV.

Simulation Layout

To illustrate the layout of the simulation space, Figure S2 is provided.
Interruptions

In the simulation, participants were interrupted twice in each patient room at predetermined, critical moments: (1) when cleaning Patient 1’s stage 4 pressure injury, Patient 2’s monitor suddenly shows that he is hypotensive (80/60), prompting Patient 2’s monitor to alarm and an overhead announcement for the participant to check on Patient 2, (2) after cleaning Patient 1’s PIV insertion site with a CHG sponge and before inserting the IV needle, Patient 1 suddenly complains of nausea and asks for a nearby emesis basin and help sitting up, (3) after creating a sterile field and lubricating the Foley catheter to insert in Patient 2, Patient 1’s pulse oximeter alarms, prompting an overhead announcement for the participant to check on Patient 1, and (4) when placing a stool specimen from Patient 2 into a specimen cup, Patient 2’s monitor suddenly alarms showing a heart rate of 50 beats per minute, although the patient reports feeling fine and this usually happens when their blood pressure drops (reading normal at 134/75) prompting the nurse to recycle the blood pressure on the vitals monitor.

IPC Practices

Verbalizations describing any MCF subcategory were coded in terms of the IPC practice(s) they described. The definition for each IPC practice is shown in Table S1.
<table>
<thead>
<tr>
<th>Practice</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand Hygiene</td>
<td>Describing when, if, or how (e.g., method, technique) to perform hand hygiene.</td>
</tr>
<tr>
<td>Cleaning Patient, Environment, or Equipment</td>
<td>Outside the context of sterility, thinking about when, if, or how to clean the patient (e.g., wiping patient, changing linens), environment (e.g., cleaning high-touch surfaces), or equipment (e.g., cleaning stethoscope, phone).</td>
</tr>
<tr>
<td>Achieving or Maintaining Sterility</td>
<td>Describing how best to maintain or achieve a sterile environment by preparing for a task, the steps to perform a task, detecting a breach of sterility, determining status of sterility, and balancing tradeoffs (e.g., maintaining sterility versus time pressure or need to leave sterile field).</td>
</tr>
<tr>
<td>PPE</td>
<td>Outside the context of sterility, describing when or if to use PPE, what PPE to use for a task or patient, or detecting issues with PPE (e.g., visibly soiled, torn, difficult to use).</td>
</tr>
<tr>
<td>Disposal/Containment</td>
<td>Describing when, if, or how to dispose of or contain (e.g., in a trash bag, biohazard bag, sharps container) a potentially contaminated item (e.g., bedpan, IV, wound dressing).</td>
</tr>
<tr>
<td>Minimizing Contamination from Contact</td>
<td>Outside the context of sterility, describing when, if, or how to avoid spreading contamination by physical touch (e.g., planning order of tasks, minimizing trips between rooms).</td>
</tr>
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