Johnson
Cornell
SC Johnson College of Business

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# Shadow Learning: Building Robotic Surgical Skill When Approved Means Fail

**Matthew Beane**[1]

## Abstract

I explore here how trainees in a community of practice learn new techniques and technologies when approved practices for learning are insufficient. I do so through two studies: a two-year, five-sited, comparative ethnographic study of learning in robotic and traditional surgical practice, and a blinded interview-based study of surgical learning practices at 13 top-tier teaching hospitals around the U.S. I found that learning surgery through increasing participation using approved methods worked well in traditional (open) surgery, as current literature would predict. But the radically different practice of robotic surgery greatly limited trainees' role in the work, making approved methods ineffective. Learning surgery in this context required what I call ''shadow learning'': an interconnected set of norm- and policy-challenging practices enacted extensively, opportunistically, and in relative isolation that allowed only a minority of robotic surgical trainees to come to competence. Successful trainees engaged extensively in three practices: ''premature specialization'' in robotic surgical technique at the expense of generalist training; ''abstract rehearsal'' before and during their surgical rotations when concrete, empirically faithful rehearsal was prized; and ''undersupervised struggle,'' in which they performed robotic surgical work close to the edge of their capacity with little expert supervision—when norms and policy dictated such supervision. Shadow learning practices were neither punished nor forbidden, and they contributed to significant and troubling outcomes for the cadre of initiate surgeons and the profession, including hyper-specialization and a decreasing supply of experts relative to demand.

**Keywords:** learning, technology, communities of practice, work, deviance, robotic surgery, training

We have known for decades that the world of work is changing and that communities of practice must cultivate new skills to stay relevant (Barley, 1996; Anteby, Chan, and DiBenigno, 2016). New business models (Barley and Kunda, 2006), collaborative practices (Leonardi, 2011), and technologies (Bailey,

[1] University of California, Santa Barbara

Leonardi, and Barley, 2012) all demand new ways of interpreting and acting skillfully in the midst of a new and shifting set of problems, and communities that do not adapt to these conditions deliver less value and lose their jurisdiction (Susskind and Susskind, 2016). Though this adaptation occurs at the team (Edmondson, Bohmer, and Pisano, 2001) and organizational (Bechky, 2006) levels, communities of practice cannot accomplish it without ensuring an adequate supply of new members capable of performing the work that a changing world requires.

But communities of practice face a dilemma here. Much consequential learning occurs through direct and increasing participation in experts' work (Lave and Wenger, 1991; Hutchins and Lintern, 1995), yet such involvement often comes at a cost to experts' quality output (Marshall, 1972; Bailey and Barley, 2011). Prioritizing trainees' involvement risks increased costs and decreased quality in the short run as trainees consume resources and make errors, and prioritizing output invokes these same risks in the longer term via a shrinking pool of competent members. Whether via shunting lower-level automotive design work to India (Bailey, Leonardi, and Barley, 2012) or moving car sales support work to a room filled with computers away from a dealership floor (Barley, 2015), available empirical research shows a decisive turn toward the second horn of this dilemma. Trainees now often make do with decreasing participation in the work that they must ultimately perform.

Technologies that allow experts to work with reduced help from trainees intensify this challenge. Communities of practice must incorporate new technologies to improve results and jurisdiction, yet these technologies are often designed in accordance with efficiency pressures, which frequently reconfigures the work in ways that concentrate control in the hands of experts without retaining a meaningful, direct role in that work for trainees (Barley, 1986; Barley and Orr, 1997; Leonardi, 2011). Adopting new technologies often means shifting simpler tasks from professionals to paraprofessionals (Marshall, 1972; Barley, 1996), limiting trainees' ability to participate in their mentors' work. Similar change also often redistributes work across time and space, which likewise limits trainees' ability to participate directly in a meaningful subset of the work (Kellogg, Orlikowski, and Yates, 2006; Bailey, Leonardi, and Barley, 2012). Generally, such reconfigurations bring new possibilities and new failure modes, and existing research does not show how communities of practice can adjust trainees' role in the work to ensure their learning. Thus, especially as technologies and related methods allow experts to work with less help from trainees, communities of practice themselves make it hard for trainees to learn.

Available research on learning in communities of practice has not focused on the ways that trainees learn to perform their work in spite of these barriers. It has rather focused on situations in which trainees enjoy legitimate peripheral participation in experts' work—semi-structured and increasing collaboration with experts on real problems involving significant risk, granted via a publicly approved role (Brown and Duguid, 1991; Lave and Wenger, 1991). Legitimate peripheral participation is clearly evident in the socialization (Hughes, 1955; Orr, 1996; Pratt, Rockmann, and Kaufmann, 2006) and learning (Harper, 1987; Lave, 1988; Bailey and Barley, 2011) literatures—after a period of formal initiation and instruction, trainees succeed because they are granted access to increasing opportunities to work near the edge of their capacity alongside experts. This works because the tasks of the next expert up the chain overlap significantly with the trainees', allowing for meaningful observation and coaching (Hutchins and Lintern, 1995; Bailey and Barley, 2011). These literatures have not explored how trainees succeed when such participation is constrained, however, let alone how learning plays out during moments of technical transition. The studies reported here fill this gap by exploring how trainees entering communities of practice learn to perform their work when efficiency pressures and technological reconfiguration of methods prevent legitimized peripheral participation—and with what consequences.

## PRIOR RESEARCH ON LEARNING IN COMMUNITIES OF PRACTICE

Communities of practice cannot persist without training new members. Competent membership allows them to tackle complex, dynamic problems (Abbott, 1988; Susskind and Susskind, 2016), expand jurisdiction over those problems (Abbott, 1981; Freidson, 1988), and maintain a strong identity and culture (Pratt, Rockmann, and Kaufmann, 2006; Kellogg, 2011). Research has shown that although formal training has an important role to play in this competence (Glance, Hogg, and Huberman, 1997; Luo, 2007), much consequential learning occurs through legitimized peripheral participation in the work core of the community (Van Maanen and Schein, 1978; Brown and Duguid, 1991; Lave and Wenger, 1991). Legitimated access lets trainees ''get it'' by ''being there'' with old hands during the work and helping out on risky tasks in ways that bring them close to the edge of their expertise. Though this theory allows for individuals cognitively acquiring portable skills, related studies have focused overwhelmingly on learning as a social process. In either case, the trouble for trainees and the communities they aspire to join is that economic and efficiency pressures, coupled with technologies that allow experts to perform more of the work without assistance, often mean dividing the work (Berg, 1997; Hinds and Bailey, 2003) such that trainees get less meaningful exposure to experts in action. Especially as these dynamics become more prominent, successful learners must find alternate routes forward.

Studies of learning in communities of practice have not focused on this problem but have instead treated legitimate peripheral participation as a given. The socialization literature is an exemplar. Van Maanen (1975, 1978; Van Maanen and Schein, 1978) showed that once police recruits emerged from the academy, all expected them to go ''on the beat'' with more senior cops where they would really ''learn the ropes.'' This was an essential and legitimized semi-structured partnership in which they drove their own learning as they helped their more senior counterparts with failure-intolerant policing—from paperwork to castigating ''assholes'' via physical violence. Bosk (2003), in his study of trainees' relationship with medical errors, showed that learning how to avoid errors of comportment was more important than learning how to avoid technical or diagnostic errors, even those that led to death. Whether it was learning the ''no surprises'' rule or senior doctors' idiosyncratic preferences for treatment of ambiguous conditions, residents learned these lessons through a legitimized role that gave them direct, collaborative, and increasing involvement in a stable body of professional work. Beyond presuming legitimate peripheral participation, studies in this tradition do not focus on technologies that allow experts to work with less help from trainees.

Studies of apprenticeship generally take the same approach. In a study of distributed cognition in the operations of a naval vessel, Hutchins and Lintern (1995) articulated how navigation trainees learn first how to take a bearing on a distant object, then to record these from someone else taking those bearings, and then to plot position and heading based on someone else's records. They showed how this overlapping responsibility ensures that anyone at any organizational level has deep expertise in the work all the way out to the empirical interface and can therefore coach these individuals and detect and correct errors. In a ten-year study of working knowledge in a community mechanic's shop, Harper (1987) illustrated his own learning as an apprentice to Willy, a master mechanical tinkerer. Through a legitimized role that gave him access to collaborative performance of the work, Harper learned a hierarchically ordered set of skills: how to use basic tools (e.g., an acetylene torch), then how basic materials (e.g., metal, wood, plastic) respond to modification attempts, then techniques (e.g., a blacksmith's weld), then elegant problem solving (e.g., learning to heat a metal chimney from the roof to induce a draft rather than punch a new hole in the roof). At each phase, Harper worked close to the edge of his current capabilities with Willy's guidance. As with the socialization literature, we gain little insight from these studies into how trainees build professional-grade skill when methodological change radically limits legitimate peripheral participation.

Two studies of apprenticeship buck this trend, but they do not illustrate how learners succeed despite barriers to participation. The first, a study of butchers and their apprentices in urban England (Marshall, 1972), showed apprentices taking jobs in hopes of learning the trade, only to find themselves shrink-wrapping prime cuts of meat without much hope of observing master butchers making these cuts. The cost of trainee errors while butchering livestock was high, and the gains of dividing labor into cutting and wrapping rooms were high, so most trainees worked for years and built no appreciable butchering skill. The second showed North American medical personnel introducing standard Western training methods to midwives on the Yucatan peninsula (Jordan, 1989). Ironically, these methods impeded learning, as they contradicted situated historical methods for performing midwifery in the region and interfered with apprentices' and midwives' efforts to simply spend time with one another as they worked. While offering limited insight into successful learning in these conditions, these studies illustrated that technological change and limited legitimate peripheral participation can impede trainees' learning.

As with studies of many organizational phenomena, the learning literature has considered learning as a process that unfolds in the light of day: practices and methods are known and approved; learners enjoy regular, shared, and increasing access to participation in experts' work; and this has wide-ranging implications for how learning occurs and key learning outcomes. A few of these studies rely on concepts related to theft, but this refers to trainees gaining skill by observing masters who are not explicitly teaching—a clear case of legitimate peripheral participation (Brown and Duguid, 1993; Marchand, 2008). Yet learning can also occur through norm- and policy-challenging practices that go unsanctioned because they allow for productive ends. Studies of such practices offer key insights into the shadowy territory that trainees likely traverse when approved means for learning are not enough. Some of these explore policy-breaking practices (Gouldner, 1954; Paulsen, 2015), while others focus on practices that run counter to norms but do not break rules (Roy, 1952; O'Mahony and Bechky, 2006). Such research has clearly shown that organizational phenomena such as organizational control (Anteby, 2008), collaborative efficiency (Bernstein, 2012), and technology implementation (Gasser, 1986) unfold in qualitatively different ways when enacted outside the bounds of legitimized practice, with consequential and different implications for organizations and the workers who inhabit them.

Learning the skills of a given community of practice has traditionally been theorized as involving increasingly substantial participation in experts' work, granted via a legitimized role. This view has implied that learners are openly offered predictable and collective access to norm- and policy-consonant learning opportunities and that these can be flexibly sequenced to accommodate differences in aptitude and risk. Considering robotic surgical training revealed a set of practices in the shadows outside the legitimate peripheral participation typical of the literature on communities of practice.

## RESEARCH SETTING

This research draws on two interleaved studies: a multi-sited ethnography and an interview-based study. The ethnography was a two-year comparative study of urologic surgical procedures performed at five hospitals in the northeastern U.S. Three of these were world-renowned teaching institutions, and the other two allowed for training rotations from these institutions. The teaching institutions could accommodate hundreds of patients, included every major Western medical specialty, and employed hundreds of physicians and thousands of nurses and support staff to deliver treatment involving the latest technologies. Each surgical discipline in these institutions supported five- or six-year medical residencies—a crucial training period allowing generalists to achieve professional-grade skill (Becker et al., 1961; Pratt, Rockmann, and Kaufmann, 2006; Kellogg, 2010). The interview study included urological surgeons and medical residents at 13 additional top-tier teaching institutions throughout the U.S.

Residents arrived at their institutions knowing they would train in a discipline such as urology and expected to leave their programs with professionally sufficient capability in key urological diagnostic frames and procedures. Generally, apprentices spent a year or two preoccupied with scutwork, rotating across disciplines and functional areas of their institution, with only minor formal opportunities to specialize. Residents then progressed to one or two years of rotation through the various areas in their discipline, performing apprentice-type functions during procedures and in the clinic. In the final year or two of residency, trainees engaged in similar work but took a more senior role and handled more complex cases. It was standard practice for residents to rotate through nearby institutions at least once (typically two times) during their residency, thus gaining exposure to different people, problems, and surgical methods.

This study encompassed two such surgical methodologies, open and robotic, each with distinct technological accoutrements. The technologies involved in open surgery are inscribed in modern Western culture: scalpels, drapes, sponges, retractors, clamps, sutures, and so on. Intuitive Surgical's da Vinci robotic surgical system consisted of three basic components: "the console" (an immersive control apparatus), "the brains" (a computing tower), and "the robot" (a 1,000 pound, four-armed surgical device).[1] Three arms on the robot held "wristed," sticklike equivalents of traditional surgical instruments such as scissors or graspers, while one arm held a stereoscopic camera. The console had foot pedals and two multi-jointed "masters" for hand control—smooth surgery required coordinated, complex foot and hand movement by a seated surgeon. The tower both translated the surgeon's manipulations of the console to the robot and transmitted a magnified, three-dimensional video signal from the robot to the binocular console display and magnified two-dimensional video from one of the camera's "eyes" to screens around the operating room (OR).

Two aspects of the da Vinci were particularly relevant to residents' learning. Intuitive designed a dual console version of its system to facilitate training. The senior surgeon could digitally delegate control of the robot to this additional console via a few taps on a touch screen embedded in the armrest on his or her console. Every training institution in my study rapidly purchased and used this dual console setup. Additionally, Intuitive offered a suite of simulator software that was either installed directly on a console in the OR or on mock consoles elsewhere in a given hospital. Either way, these simulators allowed individuals to practice via the console to perform simplified, very basic surgical actions (e.g., moving instruments in space, shifting a view, passing sutures through rings) in a digital environment. Performance on these simulations was scored and rated and could be saved.

## Doing Robotic and Open Surgery: Key Differences for Surgical Trainees

Open surgery involved an attending physician (AP), medical resident(s), a scrub technician or "scrub" (an individual responsible for setup, breakdown, and exchange of sterile materials and tissue), a nurse, and inanimate, general purpose tools (e.g., sterile garb, retractors, tables, drapes, scalpels, sutures, cautery devices). Everyone but the nurse stood within inches of each other and the patient, looking down into an incision, performing highly interdependent activities with handheld tools and without much talk. As they spent more years in the program, residents did more and more of what the lay public thinks of as surgery (e.g., cutting, suturing) while the AP held and dissected tissues by hand, set clamps and retractors, and issued directives. When there was talk in the surgical team, most of it was so quiet that it was barely audible from two feet away, given the noise from devices throughout the OR. In many institutions, the AP regularly arrived well into the procedure and left before it was complete—senior residents led up to "opening" the patient, and the AP was paged when the surgical stage was set for complex or dangerous phases of the procedure. Once that phase was over (e.g., a tumor was removed and related damage remediated), the AP backed away from the patient to fill out paperwork and departed as the residents "closed."

In robotic surgery, all (including the AP) immobilized the patient, inflated his or her belly with $CO_2$, and then attached the robot to the patient via trocars (metal cylinders) inserted in keyhole incisions. The surgeon then sat in a console 15 feet or so away to view and operate inside the patient. The resident might be at the bedside or at the console. If at the bedside (a role referred to

[1] http://www.intuitivesurgical.com/products/davinci_surgical_system/davinci_surgical_system_si/.

as ''the sucker''), the resident used a laparoscopic device—a sticklike instrument inserted through a trocar—to keep the field clear of blood, smoke, and other fluids; used the tip of this instrument to retract tissues; and passed sutures, instruments, and tissues in and out of the patient. If at the second console, the resident sat and saw what the surgeon saw through the robotic camera and ''took over'' when the surgeon delegated control to him or her. When the operation was done, all cooperated to ''undock'' the robot (i.e., remove instruments, detach the robot from the patient, and back it away) and closed the patient. Unlike in open procedures, the AP stayed in the OR and participated directly in all of these activities. The nurse, scrub tech, and medical resident were much less active and interdependent with the surgeon than in traditional procedures, though all could see the procedure unfolding on multiple monitors throughout the OR.

## RESEARCH METHODS

### Data Collection

**Study 1: Multi-sited ethnography.** My ethnographic work involved site visits and observation of surgical work in the OR nearly every week at five hospitals from 2013 to 2015, as well as recurrent formal and informal interviews with hospital staff. This study draws on 4,772 single-spaced pages (11-point font, standard margins) of data gathered during 94 surgical procedures, encompassing 478 hours of direct observation. I typed time-stamped notes documenting staff interactions and the flow of work before, during, and after each procedure, noting technology configuration and use and the roles and responsibilities of each participant. I further engaged in participant observation, regularly helping with scutwork in the OR (e.g., dealing with trash, running for supplies, turning lights on and off, helping people scrub in), training on a da Vinci simulator for six sessions, getting trained to move the robot's arms around for sterile draping, and sitting in the trainee console during procedures. I also spent informal time with staff before and after procedures. Data also included 62 formal interviews conducted in private, involving 18 surgeons, 10 scrubs, 12 nurses, and 16 residents. These typically lasted 30 minutes and were recorded for transcription. Toward the end of my study, I solicited feedback on my findings at all levels in private interviews. After incorporating responses, I presented this and a draft summary of my findings to a group of 11 staff occupying all roles at one institution.

**Study 2: "Blinded snowball" interviews.** To sample heavily on relatively rare ''successful learners,'' I launched Study 2, a ''blinded snowball'' interview study across 13 additional world-renowned teaching institutions throughout the U.S. Each AP I interviewed at my ethnographic sites supplied two sets of interview subjects: two or more colleagues with comparable experience and roles at other institutions and two residents from their own institution. One of these residents had, in their view, learned to do robotic surgery very rapidly, while the other was average or below average in that regard. I was blinded to the senior surgeon's evaluation of residents' learning success until after I had interviewed them. Enacting this protocol connected me with 33 APs and 33 medical residents. Nine of these residents were assessed as average or below average, and 12 were assessed as exceptional. For semi-independent assessment of my emerging findings, I interspersed an additional 12 interviews with residents without seeking an assessment of their capabilities. In roughly the first half of these I shared my findings on learning barriers and sought residents' feedback. In the second half, I shared the practices that constituted shadow learning and invited responses to these. I asked each AP to unblind me after all of my interviews were complete.

## Data Analysis

Though the motivation for this study preceded its implementation, the obstacles to learning robotic surgery were not clear until Study 1 began. As these became apparent, so did the reality that a few residents were managing to acquire a surprising amount of robotic skill—and concomitant time on the console—in spite of these obstacles. These obstacles and successes were only apparent as I gathered data on medical residents' (and APs') entire education—from well before residency until its conclusion. I thus settled on the period between residents' undergraduate studies through the end of their residency as my unit of observation for the study. In a year at my five ethnographic sites, I found only three individuals who had managed to make exceptional progress in learning robotic surgical technique, and while they differed greatly, the practices that they had engaged in to learn seemed quite consistent. Study 2 confirmed and deepened my initial findings: a particular set of activities and settings was associated with successful learners. Practices are therefore the unit of analysis for this study.

My analytical work iterated across data derived in both studies. This involved multiple readings of field notes and interview transcripts from my ethnographic sites, as well as multiple readings of transcripts from my blinded snowball interviews. Both of these relied on considering a variety of literatures, discussing exploratory memos with colleagues (Glaser and Strauss, 1967), and focusing on surprises and contrast (Abbott, 2004) as a way of inducing meaningful and novel perspectives that could explain the work under study. My initial analysis during Study 1 yielded a number of themes related to contrasts between learning robotic surgery and learning open surgery. Some of these centered on legitimized methods for learning and teaching (e.g., time in the OR, AP feedback), some on challenges (e.g., dramatic reductions in residents' time on task from open to robotic surgery), and others on rare productive responses (e.g., abstract rehearsal). These themes shifted over time with additional, more focused data collection and in response to interim findings. One of the most important methods for producing findings—whether manifest in the first or second study—was regularly soliciting reactions to my interim findings from participants in informal conversation, private interviews, and group presentations. It became clear that legitimized and well-understood practices for training and learning surgical skill were quite insufficient for significant progress in learning robotic surgery.

In my second study and later analysis, I focused on how residents made exceptional progress acquiring robotic skill despite major barriers to legitimate peripheral participation in robotic surgical work. I inquired more systematically here, focusing on aspects of the learning context such as temporality (e.g., sequencing of key activities), community (e.g., whether and how participants communicated about key activities), normativity (e.g., whether and how key activities ran counter to institutionalized expectations), and consequences (e.g., whether and how key activities were sanctioned). To avoid biasing responses, I likewise relied heavily on open-ended interview questions, turning to confirmatory, closed-ended questions only after my informants had volunteered key details of their learning journey. As I engaged in this inquiry, I composed and refined a process model that accounted for successful learning in my context and assessed how each resident's account hewed to this model.

Overall, it became evident that the norm- and policy-challenging yet tolerated practices I observed in Study 1 were crucial to residents' success. This led me to draw on studies of norm- and policy-challenging practices in organizations for interpretive grounding. These studies suggest that when approved means are not available for locally preferred outcomes, norm- and policy-challenging means are enacted. These means are generally performed out of the limelight and are tacitly endorsed by the broader organizational system for the results they allow. By taking these literatures seriously and through close examination of my empirical data, I derived the concept of "shadow learning": the norm- and policy-challenging, tolerated practices enacted out of the limelight that allow apprentices to learn when norm- and policy-consonant means are insufficient. This frame was an excellent match for my phenomenon and with a practice theoretic lens (Feldman and Orlikowski, 2011), as it was the more or less sequential enactment of these activities that counted for learning.

## THE QUEST FOR UROLOGICAL SURGICAL SKILL

### Barriers to Learning Urological Robotic Surgical Skill

Surgical residency had no purpose if not to produce new members of the surgical community: individuals who may legitimately perform surgery by dint of the skills to do so. To achieve both aims—legitimacy and skill—students took years of costly training, beginning with pre-medical undergraduate education, proceeding through four years of medical school, and culminating in five to six years of residency. This system explicitly began at the generalist level and presumed trainees would become increasingly specialized. Beyond addressing the critical need for extensive side-by-side practice with experts, these activities were portrayed as and presumed to be effective (Abbott, 1981; Freidson, 1988) and therefore legitimized the outcome to trainees, surgeons, and the public. Trainees needed to show day-in, day-out commitment to their profession to advance, so they paid a high price if they did not comply with and voice support for these legitimized methods for building surgical skill (Kellogg, 2012). Practical pressures to learn intensified with the shift from a 120-hour to an 80-hour work-week for residents (Kellogg, 2010), which meant that residents and APs had to make more of the practice opportunity available.

But the reality of professional work, and surgery in particular, was that pressures to innovate via new technologies and methods were also growing, and experimentation was required in order to make progress:

> The history of surgery is always that you're trying to move things forward, to find the next best thing. And you're not going to know in the beginning whether or how a new approach is more effective. It was the same with laparoscopy. [It] started in '92, and there were similar calls [as with robotic surgery today]—you should lose your

> license, you're killing patients, it was crazy. Now, if you don't do a bowel resection laparoscopically, people look at you with a little suspicion. (AP)

Beyond this, technical change to methods had allowed for finer-grained divisions of surgical work that allowed APs to do more of what they are best at while reconfiguring, and often restricting, residents' roles in the work. Surgeons and residents at all of my sites therefore faced a daily dilemma: find a way to ensure a meaningful, legitimate role for residents in the work while taking full advantage of the cost-reducing and skill-extending benefits offered by new technologies. By definition, the APs that I interviewed had discovered a way to succeed on this front with respect to robotic surgery, but it became clear that most residents had not.

## Legitimized Learning Opportunities in Surgery

From well before they arrived until they left, residents built surgical skill—the ability to use one's body to execute appropriate surgical maneuvers effectively—in a hierarchically ordered fashion. After an initial phase focused on building conceptual knowledge (e.g., anatomy, organ system function), they moved on to building embodied capability with basic materials and tools (e.g., learning to tie certain kinds of knots). More complex skills (e.g., making an initial incision, resecting a tumor) were constituted by more basic skills. The key with any skill, whether complex or basic, was that the resident had to be able to perform it smoothly in the midst of real work. Just as with many embodied skills, this required extensive repetition. I frequently observed medical students, visiting for summer rotations, tying knots in the air or on a post, for example. Complex surgical skills could not be acquired only through solitary rehearsal, however—this required increasing involvement in live procedures in the OR.

For many decades, surgeons have referred to legitimate peripheral participation as "dwell time" (Holmboe, Ginsburg, and Bernabeo, 2011) and treated it as foundational to their legitimacy and skill: you couldn't become a surgeon if you hadn't logged many, many hours in the OR. Within this requirement, everyone involved in surgery—APs, nurses, scrubs, and residents—understood the appropriate way to convert dwell time into surgical skill: "see one, do one, teach one." In other words, watch a procedure a number of times, participate in it a number of times, and then teach others how to do the procedure a number of times. As illustrated in other studies of legitimate peripheral participation, these activities were not distinct—as time went on, the emphasis of a resident's experience shifted gradually from observation to performance to coaching new hands. The structure of medical residency was tailored to this learning pathway: everyone expected junior residents primarily to observe procedures, mid-cycle residents to perform ever-more-complex portions of these procedures, and senior residents to teach and guide junior residents in surgical work, even as they continue to practice complex skills themselves.

Legitimate peripheral participation and "see one, do one, teach one" in particular were deeply disrupted in the practices of robotic surgery at my field sites, as the da Vinci surgical system allowed experts to proceed without trainees' help:

> . . . Say you were in upper Maine or something, and you needed to do a hysterectomy and you didn't have a partner to operate with . . . you have a scrub tech. You could use the robot and get your surgery done. So the robot allows people to operate without other surgeons in the room, that's the bottom line. (AP)

APs had ultimate responsibility for safety and efficacy and therefore did what the technology allowed, with significant, negative implications for residents' learning.

### Legitimate Peripheral Participation in Open Surgery

Standard open surgical technique at my field sites dictated residents' legitimate peripheral participation in the work, allowing them an effective means of achieving open surgical skill. During the beginning and end of many traditional procedures, the AP was not in the OR or stood back from the surgical field. During this time, a mid-level or senior resident led from the prep and initial opening of the patient until the procedure approached a point at which the risk and implications for downstream action were high (e.g., operating near major nerves, tumors, or highly vascular tissues). This is the point at which the nurse called to tell the AP that he or she should participate in the procedure. After arriving, the AP then worked with the resident(s) to do this part of the procedure and generally showed the way, with the resident doing what the lay public sees as actual surgical work: cutting, cauterizing, and suturing. Within this arrangement, APs delivered feedback through touch and gesture or spoke it quietly. They likewise regularly, easily, and quickly redirected the resident's focus to suit the intensity of the task and the resident's skill:

> There's more going on [in open surgery than in robotic], it's not apparent to everyone in the room, and it's easier for the attending to also move in a different direction if you're not doing something right, they can take . . . instead of 50–50, it can be a 75–25 sort of thing, basically instead of letting you get into the appropriate plane of a dissection, they're getting into the planes of the dissection and you're basically just cutting. But you still feel like you're part of the procedure and the attention is not pointed in a negative way. (Resident)

The junior resident, if present, did supportive work of some kind but was in some minor way involved in the procedure (e.g., holding a retractor, minor suturing). Then, once the risky or formative portions of the surgery that actually required the AP were complete (e.g., tumor removal), the AP said something like "okay that's it," broke scrub, and left the room or began to fill out paperwork and chat with the nurse, away from the patient. After this point, the senior resident was in charge of "closing," which involved suturing a variety of tissues together to reconstitute the patient as whole and stable, working interdependently with the junior resident to accomplish this goal. Once the patient was closed and clean, the team moved him or her to a gurney, and the residents took the patient out of the OR to the recovery unit. APs sometimes arrived at the beginning of open procedures. When they did so, they played very minor roles or consulted scans at a PC away from the surgical site.

Thus in open procedures, "see one, do one, teach one" provided an effective learning pathway: the barriers to progression from the periphery to the core of the work were many, continuous, and low, and these were routinely crossed as work could not proceed without residents' extensive participation. Junior residents got to ''see one'' initially but were easily and flexibly invited away from the periphery: they closely observed entire procedures from the bedside while doing minor surgical work. Only medical students (generally present in the summertime) were allowed to simply watch entire procedures. Mid-level and senior residents were generally in ''do one'' mode—they performed a fair amount of independent work, and the AP could not work without these residents' ongoing complementary action, as one resident explained: ''[In open surgery] you're cutting, you know they're [APs] showing you something to cut and you cut, or you're showing them something to cut and they cut it. All four hands are working together and you kind of find the ureter, you go down to the bladder, you know.''

These residents also ''taught one,'' however: in almost all cases in which a senior and junior resident worked without an AP present, the senior resident was quite talkative and demonstrative in explaining what he or she was doing and coached the junior resident through the relatively more active portions of opening and closing. Generally, the more residents did, the more they were allowed to stretch and do more complex and risky work. Past a certain point, they were implicitly granted the authority to run early and late portions of procedures, and they thus shifted to teaching before they left their residency.

Residents were expected to learn things like anatomy off-line and to practice things like suturing and even laparoscopic technique off-line, but they reported doing essentially no off-line practice for open procedures. They occasionally debriefed after procedures and talked through how to perform complex maneuvers, and some circulated relatively detailed typed outlines of a given procedure. But everyone—residents, APs, nurses, scrubs—assumed that almost all of the important learning happened through increasingly consequential work in the OR and that this was right and proper.

## Failure of Legitimate Peripheral Participation in Robotic Surgery

One of the main reasons APs relied on residents to perform open surgery is that these residents had several years of embodied practice with basic techniques such as establishing and maintaining a sterile field, suturing, retracting, and making incisions, and could therefore perform these fluidly under pressure. But most residents practiced robotic surgical technique a few hours a year, at best, and they were far less fluent with basic robotic technique:

> Robotically, yes, you can learn a little bit from watching, especially in the beginning, but until you have your hands in there, moving tissue around—those are robotic hands—I think you're only learning 5% of your full potential. And for that 10 minutes where you're doing the steps [robotically], that's when the other 90% of the learning comes in, but you're only doing it for a very short time. (Resident)

> In robotic surgery if you get into the same scenario [nicking an artery], the actual process of tying a knot [to remediate it] is not instinctive. It's different, because it's not your own hand, it's not your own wrist, it's not your own fingers. Even if you were able to throw a stitch across that bleeding vessel, you have to think how to tie a knot when you're doing it robotically. (Resident)

Beyond this limitation associated with basic robotic skill, standard robotic surgical technique at my field sites made it practically impossible for residents to effectively learn robotic surgical skill through peripheral participation. The medical resident, at best, got the patient onto the surgical bed before the AP arrived in the OR. The AP led the activity of positioning the patient, marking initial surgical sites, making small incisions in the patient, and attaching the robot. The AP likewise stayed after the core of the procedure was done to lead the undocking of the robot and all but the final rousing of the patient (perhaps 10 minutes of work). Attaching and detaching the robot were seen as critical opportunities for failure—if workers didn't position the patient and equipment appropriately, the risk of catastrophic injury was high. Trocars could puncture or tear blood vessels or organs if inserted or removed improperly and strongly determined the ease and range of surgical action once the robot was attached, for example. As with takeoff and landing in aviation, the riskiest phases of a procedure were the beginning and the end, in contrast to open surgery, in which the danger was in the middle (of the procedure and the patient).

All this meant the practical elimination of the AP-free portions of a procedure. For the resident, this meant a dramatic reduction in opportunities to ''do'' parts of the procedure without significant supervision and a near elimination of opportunities to ''teach'' other more junior residents. These issues alone presented a significant threat to residents' acquiring robotic surgical skill through legitimate peripheral participation, but these dynamics were compounded by the way that APs supervised and taught residents during robotic surgical work.

## Helicopter Teaching in Robotic Surgery

In significant contrast to open procedures, handing off control to a resident in robotic procedures was, for practical purposes, a binary choice. The AP was either at the console, in control and doing all the operating, or delegated complete control to the resident with a light tap on the armrest touchscreen. APs also regularly used this feature to pause the work: if safely positioned and left alone, the robotic apparatus held patients' viscera fixed—something that took great cooperative effort and skill in open procedures. Many surgeons and residents used a driver's education analogy to describe instruction in robotic surgery: the surgeon put the resident in the driver's seat for practice but retained the ability to hit the brakes at any time.

> It's like driver's ed. It's harder than you think. [You're] sitting side-by-side and [the] surgeon's doing something, swaps the controls [for you] to try to do the same thing. There's a lot more to learn, and it's not like you have someone behind you showing you how to, like you do during an open case. Even with the dual console. (Resident)

And just as in driver's education, surgeons relied almost exclusively on verbal feedback and coaching to help the functionally independent resident navigate the surgical field. Unlike in open procedures, this ''help'' came in great volume and intensity. The da Vinci system magnified the surgical field by up to ten times actual size, allowing error-intolerant APs to perceive a new class of surgical errors. Though typically very minor, they appeared large on screen, and APs were compelled to intervene:

> 2:24 PM
>
> C (*AP, at primary console, just after giving up control*): You can see why you're dissecting, between the sv [seminal vesicles] and vas [deferens] earlier, and now you're slowly beginning the process of making hamburger meat, that's where the resident chops up the vas deferens to the point where it's a mess. And I have to grab it. If you're going to grab it, grab it like you mean it, none of this little baby shit, take a big grab. Bipolar [referring to cautery instrument], aaeeeeh (*making sound effects*), now, eeeeh bipolar eeeeh, you're not going to even . . . cut to the left, cut to the left, cut to the left, cut to the left, cut to the left. (*Resident cuts.*) Does that make sense (*referring sarcastically to the resident's cut*)? So we don't care about backbleeding?
>
> K (*resident, operating at second console*): Okay.
>
> C: Okay, now go to the top, spread it a little, not like an animal, just a little, there is no law that you must spread maximally, cut to the left, cut to the left, cut to the left, you're always cutting behind what you burned. Good. Now, tip to the left. K, I promised you two cases ago that I wouldn't walk you through this anymore. Get that bleeder to the right. Get that bleeder, that's where you're going to get the nerves. Bzzzzzzz. That's it, right there, good.
>
> C: Good job, that's nice, stay right on top of the sv. Stay right on top of it. Nice, cut.
>
> C: Allright, you're done for now (*takes control*). 2:27 PM. (Field notes, 1/14/2015)

As this extract illustrates, APs' verbal coaching was audible to everyone in the room. Further, the surgeon could make ''digital instruments'' appear in the resident's view of the surgical field, then point to certain structures and indicate directions and speed of potential motion, but in every case this was done to accentuate a point that the surgeon was making verbally. Residents experienced this kind of learning environment very differently from open procedures:

> If you're on the robot and it's [control] taken away, it's completely taken away and you're just left to think about exactly what you did wrong, like a kid sitting in the corner with a dunce cap. Whereas in open surgery, you're still working, so you have less time to focus on that negative time, you're sort of working into a new area, you're still doing something, you have to continue to focus, because you're still operating, you're not completely out of the game at that point. You're sitting on the corner of the bench rather than in open surgery you're swimming at one end of the pool or treading water in the shallow end, but you're still swimming. (Resident)

And as the elapsed time of three minutes in the above extract also illustrates, this translated to a dramatic drop in time on the surgical task unless the resident demonstrated extreme competence right out of the gate. The irony was that achieving such competence required significant console time. To begin with, most residents spent the bulk of their residency only ''seeing one.'' As one resident said, ''You also have this hate relationship with it because for the last four years you've been watching other people do it. For me [by my chief year], I had been on the robot a few times, very scattered and not very long lasting. And you really don't get a good sense of it when you're doing it intermittently.''

For the procedures I observed (4.5 hours on average), residents performed surgical work for essentially the entirety of each open procedure, whereas they had 10 to 20 times less time on surgical task for robotic procedures. Beyond this, the few minutes that residents were allowed on the console were closely supervised and critiqued by an AP. APs were highly skilled and bore ultimate legal and moral responsibility for surgical safety and efficacy, and major errors were much harder to correct quickly than in open procedures:

> In open [surgery], if you put a hole in the iliac vein, yeah, it's a big problem, but you can put your finger there, compose yourself and get control. If you cause that in a robotic procedure, the patient could hemorrhage before you regain visualization. If they [surgeons] think they can do it by themselves safely, they're not going to want to take that risk [letting the resident operate]. (Resident)

> It's not going to be bloodless every time, but some faculty, as soon as they see you off course, they say ''I got to get you back on'' and when they sit down at the console, it's never just to get you back on course. (Resident)

All of these pressures translated into APs intervening frequently in residents' attempts to operate, both verbally and by taking and granting control:

> Q (*AP, at primary console observing*): Do you think I was happy about that move or no?
> J (*resident, operating at second console*): No.
> Q: Do you know why? Because you're taking your bipolar [cautery instrument] and ramming it into the bowel. If you're going to do some blunt dissection, pretend like you've done it before. STOP, STOP doing that! Take a break (*takes control*). I say don't do that, you do it, don't do that, you do it, I don't know how I'm not supposed to get frustrated. This isn't a bladder. No more using this hand for anything except to pull things down. (*Gives control back, resident begins operating.*)
> 8:55 AM [closest timestamp to extract start]
> (*Q keeps head in console.*)
> Q: Back up the camera for perspective, back it up. Good.
> Q: Back up the camera for perspective. I want you to start going the other way for perspective, no, no, no, don't do that again please. You start going there and you go to the left (*takes control*); it's like painting a wall, you go left to right, then right to left, you go like this (*demonstrating*). You want to try it? (*Gives control back.*)
> Q: God, stop (*stands, out of console*). I just can't stand to watch that. I'll give you one last chance on this, Dr. J. It doesn't look good to shove your instrument into the bowel. If you take over, why don't you pull up, do anything that doesn't put you on top of the bowel; this is your fifth warning.
> J: It's all right.
> Q: That's the line, right there, see where the elbow ends.
> Q: Now you're going in the wrong plane. (*Takes control.*) Take a break.
> 8:59 AM (Field notes, 03/28/2014)

Thus in robotic procedures, the barriers to progression from the periphery to the core of the work were few, discrete, and high and were infrequently crossed as work could proceed without residents' help, and it was exceptionally difficult to recover from residents' errors. As a consequence, well-intended surgeons relying on a new technology that allowed for increased supervision and control ended up micromanaging apprentices away from legitimate peripheral participation in the work. This and standard approaches to performing robotic surgical procedures outlined above prevented residents from learning via legitimate peripheral participation. Opportunities to actually do and teach surgery were reduced by an order of magnitude or more, and (largely critical and imperative) AP coaching was both public and far more frequent, greatly decreasing opportunities for residents to struggle near the edge of their capabilities.

## Problematic Implications for Residents' Learning and the Surgical Profession

Most residents did not overcome these barriers enough to acquire professional-grade robotic skill, though they left residency having been legitimized in this regard: completing residency conferred a license to perform *any* urologic surgical procedure. Everyone expected them to acquire the bulk of their skill by watching, doing, and teaching robotic surgical work alongside experts, and trying to fulfill these expectations within the bounds of legitimized robotic surgical practice did not produce sufficient opportunity for practice, independent struggle, and instruction. As a result, all but a few residents felt less competent at the console than they did in traditional procedures:

> There's a different level of confidence [between open and robotic work]. I know that the outgoing chief feels very comfortable doing a nephrectomy [kidney removal] open, but I've heard them say that ''I don't know if I'll do robotic or laparoscopic nephrectomies'' because the level of confidence is not there for that modality. And I know that they won't be doing robotic prostatectomies—they said that they won't—but they said they would do open prostatectomies if the situation would arise. (Resident)

Yet everyone who completed a residency was legally and professionally legitimized to independently perform surgical work in their discipline, including robotic surgical work. And so, confident or not, many new surgeons performed such work, but at very low volume: as of 2015, the average urologic surgeon in the U.S. who did any robotic surgery performed one robotic prostatectomy a year (Chang et al., 2015). So most surgeons did not do the work they needed to do to keep skills fresh (Jenison et al., 2012), nor had they undergone the requisite amount of training to cement their competence in the first place. These dynamics had negative implications for the development of surgical skill in *both* open and robotic techniques:

> It [robotics] has the opposite effect [for learning]. If you take a look at X who trained in Oregon, and Y who trained at Ohio State [top robotics programs], they are not good robotic surgeons. As a result, they have to come here and do them with B [robotics expert]. They trained in [top] programs that teach robotic surgery. And they suck now. I mean these guys can't do it. They haven't had any experience doing it. They watched it happen. Watching a movie doesn't make you an actor, you know what I'm saying? In addition, their [residents'] exposure to open surgery has been altered by the presence of robotic surgery. The younger guys become deficient because they watch a lot and do nothing on the robot, and they're becoming deficient in open because most surgery's going robotic and less and less is open. So that's shit and bad luck. I mean you stink in robotic and now you're stinking in open because you're not doing enough. (Chair, Urology)

Residents were aware of this problem but had very little influence on the structure of their residency—they were focused on fulfilling its requirements so that they could move on to professional practice. As one said, ''Sometimes the attendings don't feel comfortable doing that given the fact that they cannot interact with you directly or cannot show you or also intervene if it's indicated. So that's the thing that limits your education in terms of case numbers and time on the robot." When I asked how the resident compensated for that, I was met with a blank stare. "What choices do I have? I have no choices."

Further, the deep differences between robotic and open surgery made it very difficult to fulfill the requirement to reach competence in both. Surgeons specialized in one or the other and then ended up performing procedures in that modality almost exclusively. They could not, in good conscience, select a modality in which they had not specialized, even if that approach were indicated for a patient. APs and department chairs were also often aware of this problem, but the liability and efficacy concerns outlined above presented a strong barrier to change:

> We're trying to deal with this, it's not like we don't understand it. But how as a department chair do you go to R and P [top surgeons] and say "Hey, you guys are not teaching, you gotta let them do more surgery." And they say "Well, what if they fuck up my patients? I can't do that." I don't have the right then to say "You must do it." Because they're right too, because their nuts are in a noose, and they have a patient to worry about, and they got malpractice to worry about, and they have outcomes to worry about. (Chair, Urology)

Residents thus faced a significant double-bind: they were obligated to visibly comply with legitimized "see one, do one, teach one" methods of peripheral participation to learn, yet standard robotic surgical practice and AP approaches to teaching during live procedures greatly delimited and reconfigured their access to the practice field. It was therefore extremely difficult to engage in legitimate peripheral participation in a way that led to sufficient robotic surgical skill. Given these barriers, a small minority of residents found a way to competence through a different and novel set of practices that stood in significant tension with the norms and policies of the surgical profession and hospitals.

## Shadow Learning as a Critical Pathway to Robotic Surgical Skill

Just as they demonstrated effort in legitimized (yet ineffective) learning modalities, the relatively small proportion of medical residents who were exceptionally successful in acquiring robotic surgical skill found alternative ways forward via shadow learning. They all reported engaging extensively in three interdependent practices, roughly in sequence: premature specialization, abstract rehearsal, and undersupervised struggle. Their "average" counterparts did not report engaging in all of these practices extensively—indeed only four made any mention of them whatsoever, as shown in table 1. Shadow learning differed from legitimate peripheral participation in four key ways: its constituent practices ran counter to norms and policy, these were enacted opportunistically and in relative isolation, and they provided the competence required for access to work involving experts.

**Shadow learning: Premature specialization.** In the U.S., almost all residents ultimately went on to jobs that required them to perform a wide variety of surgical and nonsurgical work in their discipline, so everyone insisted on an early generalist education. The right and proper time for prolonged and intensive exposure to any specialized surgical technique was therefore late in

**Table 1. "Blinded Snowball" Informants' Reports of Extensive Engagement in Shadow Learning Practices**

| Successful learners | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Premature specialization | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Abstract rehearsal | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Undersupervised struggle | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Average learners** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | | | |
| Premature specialization | ✓ | | | | | ✓ | | | | | | |
| Abstract rehearsal | | ✓ | | | ✓ | ✓ | | | | | | |
| Undersupervised struggle | | | | | | | | | | | | |

surgical residency. By contrast, trainees who acquired notable robotic surgical skill began specializing in this technique years before they arrived at their residency:

> We have a four[th year resident] here now who happened to do research time in a robotics lab before she started residency, so she's like way on this side of the curve. I can already tell, she's great, she's better than most chiefs, so but she spent significant amount of her life, like one to two years, in the robot lab at [hospital X] doing research, so it's like cheating, you know? (AP)

> The very first time I was on the robot—the University of X had a robot, and a guy who was a robotic surgeon was one of my [medical school] research mentors, and when they were done with the case, he would let me move around the robot arms around inside [the patient], move the camera and clutch pedal and different things like that, I wouldn't really pull or push on any of the tissues at all, or cut anything, but I got at least a little bit of the muscle memory involved. [Also] they would use children's toys, so you would play the game Operation with the robot in your off time. So even when I started as an intern, it wasn't like I was sitting down at it for the first time. (Resident)

Residents engaged in premature specialization in three key and often overlapping ways: participating in related research, receiving specialist mentorship, and participating in the work itself. First, medical students typically spent six months to a year learning and applying research methods in a standing project via a research assistantship. When focused on operative technologies such as the da Vinci, such projects required medical students to develop deep familiarity with such technologies, including how they were operated, users' opinions about them, related outcomes research, and differences in the profession as to how to use them to achieve key outcomes. Successful learners cited this kind of premature, intensive exposure to robotic surgery as crucial to their learning. Second, successful learners specialized prematurely by matching with a mentor focused on urologic robotic surgery. While successful residents all reported such matching, this was not typical: medical students tended to find mentors who worked in areas of interest (e.g., urology), but by design they were not yet focused enough to find mentors focused on a particular subspecialty (e.g., urologic oncology), let alone a method for performing related procedures. Finally, premature specialization involved extensive direct observation of robotic surgical work, often including use of the da Vinci system itself during live procedures and/or in simulated exercises. This extremely early access to robotic surgical work was typically granted through participation in related research or by a specialist mentor.

These activities violated norms and policy on two fronts. First, residency and medical school—and to a certain degree undergraduate education—were zero-sum games in terms of the time available for learning. So the amount of focus outlined above came at the expense of generalist learning, personal life, or both. Generalist learning was a more likely target for this subtraction, given recent restrictions on residents' working hours. Second, given the premium put on a generalist education, many presumed that students were not far enough along in their education to extract meaningful skill from premature specialization in robotic surgery, let alone to participate in a way that was safe and helpful. According to this logic, successful learners of robotic surgical technique begin "seeing one" (and sometimes "doing one") years before they should, wasting resources and slowing their progress.

**Shadow learning: Abstract rehearsal.** Abstract rehearsal was the second practice that allowed residents to learn robotic surgery. Residents engaged in it in three ways: practicing basic skills in rudimentary computerized simulation, analyzing recorded procedures for general familiarity, and analyzing challenging segments of recordings just before related work. The first of these—practicing via simulation—was particularly crucial:

> The difference [between me and all the other residents] is that I used that simulator pack every day for a while before I actually started operating that much, and that should be required for everyone honestly, because it made my transition a lot easier. Most everyone is learning what they're learning in the OR, during live procedures. (Resident)

Successful learners used available simulator technology extensively for gaining basic familiarity with the new, disembodied control modality presented by the da Vinci system. Until exposed to the da Vinci, residents had learned to use their bodies to control precise professional activity directly. A move of the finger corresponded immediately and directly to a move of the finger in their work, directly generating change in the world with direct tactile and visual feedback. Not so with the da Vinci. Before they could operate on a patient, trainees had to master a new bodily grammar for their professional work:

> You hand a kid that plays Xbox all the time any game, he's come to be good at it because he doesn't have to think about where the buttons are. Then he figures out how to be good at a game not how to operate the controller. And that's what it is with the da Vinci too. Once you know how to operate the controller, that becomes mindless and then it's the surgery which is like any other surgery. (Resident)

Most programs required residents to practice on the simulator, but these requirements were scant (two to four hours per year was common) and only occasionally performance based. This was grossly insufficient for fluency with robotic grammar. Those who were successful often invested many tens and sometimes over a hundred hours of discretionary time on the simulator early in their residencies, and this gave them the basic fluency required to earn console time:

> I specifically said [to a new resident] ''You have to use the simulator. You must use it. When you get on, you want to be there because otherwise they're [the AP] going to pass you up.'' So if you've had hours in the simulator, you're going to look like you know what you're doing, and they'll let you do more. Well I let her get on one, one of these cases, and she looked like she knew what she was doing, and the attending let her go, and she did well. (Resident)

While most residents had to use OR console time to simultaneously work on basic robotic fluency and the sequence of activities associated with a procedure, successful learners could devote much more of their attention to higher-order activities such as transitioning from one portion of a procedure to another, asking the AP questions, or directing bedside assistants. It was impossible to undertake such activities without a strong command of robotic control grammar, and these higher-order activities were therefore particularly valuable for earning extended console time: making transitions and asking good questions provided insight that facilitated next steps and impressed APs, and a well-guided bedside assistant provided good exposure, making the resident's work easier and therefore also more impressive to an AP.

Successful residents also analyzed videos of previous procedures. In the beginning of their learning, they scrutinized these extensively to get a holistic sense of a given procedure:

> You can watch videos on YouTube. The guys that operated there had a video, so I watched that video, I probably watched it, I don't know, 200 times for an hour-long video. A lot, a lot, *a lot* of hours watching it. It lets you see his moves and where his hands were going, and how he did things, how he was retracting things. (Resident)

But this practice ultimately hit limits—recordings were often made public because they were pristine, best-in-class work that involved relatively little uncertainty or struggle. As their skill and need for nuanced insight deepened, successful learners focused their analysis on portions of a procedure that they wanted to improve on and did so to prepare for an upcoming procedure: ''I think there's good value in watching other people do surgeries online, and even watching it before you do a procedure, kind of like doing a pregame kind of thing'' (resident).

In contrast to those who successfully acquired substantial robotic skill, most residents indicated that simulation and online video were neither useful nor appropriate means of preparing for real surgical work, as they were too abstracted from the actual work:

> They would like us to have more familiarity with the robot, with all this simulated time and time outside the operating room, and there are these . . . exercises, they're not operative simulations. They're kind of silly. And I don't think they translate as well as the senior guys think they would. (Resident)

APs had mixed but generally negative views on simulation and video analysis. On the one hand, these are the individuals who built in the requirements mentioned above—so on some level they were committed to the idea that simulation could aid in the acquisition of foundational skill. On the other hand, APs indicated that "real" learning occurred in the OR and that any hopes of acquiring substantial skill via simulation were doomed to failure because they weren't close enough to reality:

> There is a simulator that allows for guided surgery in reverse. An expert case, a prostatectomy, goes through the whole thing, fingers, and feet. I think it's bullshit. I think I could have my kid do that, and I'm not sure how many neurons would be developed. Every case is different. It's impossible—very difficult to program all the different layers to make it realistic, so many layers, so many chances for bleeding, injury. (AP)

Interestingly, APs reported watching videos in the 1990s—recorded at great expense and available only via DVD and VHS—extensively as they navigated the transition from strictly open surgical technique to laparoscopic technique: "I've got bins, look at this [*gets box*]. VHS tapes! I can't even play them anymore if I wanted to. How many times did I watch them? They're like treasures to me now" (AP).

Beyond the negative normative tinge to learning through simulation and video, residents' daily responsibilities and the da Vinci technology were configured in ways that made practice on simulators and watching videos impractical:

> I don't think anyone uses the simulator—we have simulator packs on all of these robots, and I don't think a lot of people use them. Even though we were supposed to. It's just crazy that they have these 65-thousand-dollar simulator packs, like the one here, I tried to get on it, and no one knows the password. [Also,] they're in the OR, so the OR has to be open to use them. They do have that sim center [a quarter mile from residents' normal work area], but I don't ever really go back there. (Resident)

As this resident said, most simulator practice required access to an empty OR, a da Vinci console that was plugged in, and a "simulator pack": a high-end computer with simulation software, attached to the back of the console. Generally, ORs were empty only in the evenings, so simulation time required residents to stay after hours or take time away from "above and beyond" duty on night rounds (e.g., checking on patients at the bedside). Alternatively, some elite institutions had simulation centers to allow for a variety of kinds of practice. These sometimes included a separate training console with simulation capabilities. These were often physically remote, however, and gaining access required jumping through a number of administrative hoops. In most cases residents did not rely on such centers any more than they had to in order to fulfill (minimal) mandates for simulation practice.

**Shadow learning: Undersupervised struggle.** Through premature specialization and abstract rehearsal, successful residents gained the skill required to get access to a third shadow learning practice: struggling near the edge of their capacity with limited supervision by expert APs. As evidenced above, helicopter teaching was one of the main—if not the main—barriers to legitimate peripheral participation as a means to develop robotic skill. Though no residents reported deliberately attempting to dodge such "help" in their surgical work, the most successful among them indicated that they performed robotic surgical work with limited supervision from expert APs for lengthy periods. Ironically, while APs prevented it via helicopter teaching, many also cited undersupervised struggle as crucial to their own skill development:

> P (*resident, sitting next to console*): I don't think I could see this [tissue plane], you could show me this ten times. . . .
> R (*AP, head in console, operating*): Some of it was when I was learning this and I struggled, and I tell you my solutions. . . . When I was a fellow, they were doing their cases in Mexico, they asked for someone, everyone said no, and they ended up with me. They said can you go to Mexico and I said sure (*stops operating, removes head from console, turns to resident*). Did I tell you this?
> P: No.
> R: There were 3 [senior Mexican] surgeons doing 13 surgeries in 8 days, so *I* was there in the OR *teaching* these surgeons and a couple things made it hard. When we ran out of instruments, that was it. And I tried the American thing where you complain and you get what you want, and they were like "no no no," so we were having to manually override the system so we could use expired instruments, we didn't have rv sutures and we had to use sh needles. . . . Out of that week and out of necessity I had to get people out of cutting the prostate in half, cutting the gastric, all but the most major snafus, upper gastric injury, it was a crash course of how to get people out of trouble, and so for each step I had to take them out of the console and walk them through it verbally, it was like the wild west, so that week I learned *so* much.
> P: I can imagine. (Field notes, 6/3/2015, 12:55 PM)

Successful residents engaged in undersupervised struggle in three ways: working for superstars, working with lower-skill experts, and working at institutions with less cost strain. In each case, successful residents did far more surgical work near the edge of their capability with little supervision than other residents. This forced them to independently recover from non-catastrophic errors far more frequently than those who did not engage in undersupervised struggle, driving them harder to practice for each procedure. Both of these activities had significant positive implications for their robotic surgical skill.

*Undersupervised struggle: Working for superstars.* Some successful residents worked for one of a very few superstar robotic APs (not the more numerous "excellent" APs). As with superstars in other professions, these APs were responsible for a wildly disproportionate number of procedures per year compared with most other APs. A typical high-quality prostatectomy took 3.5 to 4 hours, for example, allowing merely "excellent" institutions to perform, at most, three prostatectomies in two shifts. Superstar robotic surgeons completed between six and seven such operations in the same timeframe. They achieved such volumes by running multiple concurrent surgeries, relying on residents to perform and supervise the bulk of each procedure. Residents so unusually entrusted with life-and-death responsibilities reaped significant dividends in terms of learning:

> You would do simple parts of the procedure first. Our goal was to do that portion of the procedure independent—meaning no one else was in the room, you start the case, you dock the robot, and you get to that point then you call the boss [AP], and the boss finishes it off. 4th year we did more. Chief year, pretty much do the whole thing, the boss would maybe come in and look at it. A lot of it was autonomous. And we were very good about not going rogue and all that stuff. And whenever you got

> stuck, the boss would come in and show you how to get out of it, or you'd call an upper-level resident and they'd show you how to get out of it. So it was more a directed apprenticeship model with independent time to kind of figure things out, you know? There's no one telling you where to cut. You've got to manage bleeding on your own, and you figure it out. By the end of it you're doing it all yourself. We had high volume and that's what really helped you out. (Resident)

It is key to note that this resident's experience was typical at his institution. At institutions with merely ''excellent'' robotic APs, such autonomy was never granted intentionally and would be impossible to achieve accidentally, as each AP was responsible for the entirety of each procedure. Superstar APs simply did not engage in helicopter teaching with much frequency. To the contrary, direct AP supervision of resident surgical work was minimized to allow for high throughput. This dramatic difference in undersupervised struggle during surgical work greatly accelerated residents' robotic surgical skill.

The above quotation also encapsulates several important aspects of unsupervised struggle for residents in superstar-led robotic surgical programs. First, many of my informants indicated unease with the practice, and nearly all acknowledged that it broke policies for AP supervision during surgical work. Speech dysfluencies (e.g., mid-sentence pauses, broken words) were most common during these portions of my interviews. Second, this was not truly *unsupervised* struggle: expert help and accountability were never far away, and residents sought them when they got into surgical trouble. Third and nevertheless, actual struggle was intense: residents bore life-and-death responsibility for their patients during these periods of work:

> Having nobody in the room and you're in the hot seat, I mean I've had times where you're sweating, you're leaning on the console, the boss [AP] comes in after you and is like ''Whoa, whoa, whoa, you've been nervous here on that bleeder, huh?'' And I was like ''Yeah but how'd you tell?'', and he's like '''Cause this is all sweaty.'' I think, having some time to flounder a bit and get yourself out of it in a safe manner, I think that that helped me out a lot. That's how you learn stuff, really. Versus having someone show you, you don't even realize that you don't get to do it, you know? (Resident)

Given that they were working near the edge of their capacity, patient anatomy and next steps were somewhat ambiguous to these residents, and they had an imperfectly embodied capacity to execute next moves safely and elegantly. They were rarely relaxed and jocular while operating, as APs sometimes were; more often than not they were tense, focused, and reasonably silent.

*Undersupervised struggle: Working with lower-skilled experts.* Most of the successful residents in my study secured residencies at top-tier institutions with merely ''expert'' AP robotic surgeons and so found undersupervised practice opportunity by collaborating with APs at their institution with less-than-expert-level skill in robotic surgical methods. These APs were less able to detect quality deviations in residents' surgical work and were aware that these residents were being trained by true experts. They were therefore far less likely to engage in helicopter teaching:

> What has really influenced my training is by having other attendings within our own institution that are not as experienced or proficient as he [X, true expert AP] is. The attending that's on that service I think probably feels that I do the case as well as he

can so he'll allow me to do much, much more and he'll actually defer to me a lot of times, and say ''Well oh what does X do, what do you want to do?'' And I can do it, and he allows me to do a lot more of the case, and that builds a lot of confidence and experience in a way that I would never do operating solely with X. (Resident)

It was relatively rare for residents to find such a gap in AP robotic expertise within their own department (urology). Rather they found APs with less robotic expertise as they rotated through other departments (e.g., colorectal, OB-GYN, pediatric) during their first, second, and third years of residency. Because urology had a nearly ten-year robotic head start on every other surgical discipline, APs in these other departments almost always were relatively new to the system and therefore allowed urological residents to operate early and often:

I had even been on the console multiple times before with colorectal, when I was an intern. P [new colorectal robotic surgeon] had just started and was just doing his first robotic cases, and I was on his service at that time, so I ended up bedside assisting for him on multiple cases. And while I was there, I asked him [for console time], and at that point I had just used the simulator. And he let me do some steps, and it went well, so in future times he let me do it as well. (Resident)

As in the two quotations above, successful residents indicated that such rotations went beyond the absence of helicopter teaching. APs on these services realized that they themselves were learning and could stand to gain something from residents who had more direct contact with expert APs and who demonstrated solid basic robotic capability.

*Undersupervised struggle: Working at institutions with less cost strain.* Successful residents also got ahead by working at institutions with lower cost strain. Top-tier surgical training programs required residents to spend a number of months in their fourth, fifth, and sometimes sixth years at nearby institutions with lower cost pressures and/or quality standards. These rotations allowed residents demonstrating aptitude and interest to perform robotic surgical work with far less supervision than at their home institution. As one AP said, ''I think especially the [non-elite hospital] rotation, they get a little more hands-on experience, I think unfortunately—not unfortunately—fortunately for them, but maybe unfortunately for the patient, because the competency level of the attending's not very good.''

As in non-urological departments within residents' home institutions, APs in these institutions were less skilled with the da Vinci system and knew these residents were being trained by APs who were far more capable and productive than they were. When successful residents demonstrated significant basic capabilities garnered from premature specialization, abstract rehearsal, and prior undersupervised struggle, these APs granted them significant autonomy. Successful residents therefore got extensive undersupervised time to build their robotic surgical skill near the edge of their capabilities:

Then I went to [non-elite hospital] and got a lot of experience on the robot and . . . I think it was there where it kind of like clicked, and I stopped having to think about what am I doing with my hands and clutching and moving the camera and stuff like that and I started thinking about the surgery. So then I got a lot more exposure, and then coming back and in my chief year, so I did a lot. (Resident)

These institutions experienced less cost pressure than elite institutions, which meant less urgency to perform procedures quickly and, in turn, greater willingness to allow (slower) residents to practice during surgery. Beyond this, such hospitals and their patients imposed less pressure with respect to liability, commitment to top quality, and requirements for AP involvement in procedures, which also increased the opportunity for residents to engage in undersupervised struggle:

> There's just an understanding for the attendings that these aren't their private patients who have sought them out. It's just kind of a tradition for residents to do a lot more there, without much supervision. Also, at a lot of [elite] hospitals the attending is required to be in the room the entire time, whereas at [non-elite hospitals] the attendings don't have to be physically in the operating room. I think [non-elite] surgeons in general, if they're there, they'll do something, but if they're not there, they'll trust the resident to proceed safely. (Resident)

This reduction in supervision and increase in autonomy allowed skilled residents to ''teach one'' to junior residents as well:

> The first time I did that case at [a non-elite hospital], I did the whole thing, and the attending was obviously there, and the case went beautifully, you know, every now and then it goes like butter, and the whole case took three hours, it was very nice, beautiful dissection, and he was like ''okay, I trust you.'' He saw I could do it, I didn't need more practice taking the bladder down, so he was okay with me delegating that part of the case [to the junior resident]. (Resident)

When junior residents were present and APs were not, senior residents taught the junior residents almost by necessity—they needed these junior residents' help at the bedside. While this occurred regularly during the beginning and end of open procedures, when APs were present such resident-to-resident teaching essentially ceased. Robotic surgical work at non-elite hospitals allowed residents to perpetuate this practice. Teaching while operating was no simple task—this required the presence of mind to note when a junior resident might get involved, performing the surgery in a slightly exaggerated way to make certain points clear, and leaving the surgical field in abnormally pristine and obvious condition for a junior resident as he or she sat at the console. So this teaching burden added a new layer of undersupervised struggle both for the senior and junior resident, offering important skill development possibilities.

### Consequences of Shadow Learning

Engaging in shadow learning led to one clear consequence for robotic surgical trainees: they got unusually quick and deep access to risky work that offered relevant and exacting feedback (Hogarth, 2001), becoming unusually skilled in the process. These residents therefore ''succeeded'' in that they were ready by the end of their residency to competently and confidently perform robotic surgical work on their own. Beyond this, the routine enactment of shadow learning also led to three outcomes that were quite problematic for shadow learners, their cohort, and their profession: hyperspecialization, fewer learning opportunities for less-skilled residents, and limited learning.

### Consequences for shadow learners: Hyperspecialization

> In the states, [superstar robotics hospital] is a boutique situation . . . the rest of the disciplines are like hostels. Hyperspecialized, that's what people want in the States, not like that in Europe, you have to be able to do a bit of everything. But people here want to know ''how many of these have you done''? (AP, former resident and fellow at this hospital)

There were at least six and perhaps as many as 15 superstar robotic urologic surgeons on the planet during this study. Beyond these slots, every surgical resident, no matter how specialized in robotic surgical technique, would land in a job that required a diverse urologic surgical skill set. After graduating, most successful residents would find themselves doing procedures such as open partial nephrectomies, TURBTs (trans-urethral tumor removals), laser lithotripsies, and vasectomies, all of which required significant nonrobotic skill. Yet residents who engaged in shadow learning for robotic skills—premature specialization, abstract rehearsal, and undersupervised struggle—ended up sacrificing opportunities to broaden their skill set to match their likely future jobs: ''When I did my rotation through the clinic, you can choose the cases you do, so I just decided that since this is basically the mecca of robotic prostates, I was just going to do as many robotic prostates as I could and really didn't see a lot else'' (resident).

Beyond this generalist–hyperspecialist mismatch problem, residents knew on some level that they were playing a winner-take-all game with respect to skill—the returns to superstar-level capability were wildly disproportionate to those at the merely top-tier level. In response, many of the successful residents in this study indicated that they needed a fellowship—one or two more years of training beyond their residency—to enter professional practice: ''And that's why most people, if you really want to do robots in your practice, you're really forced to do a fellowship for a year or two. I'm going to do it [robotic cases] probably but I'm not going to do complex cases because I really don't have the experience'' (resident).

Finally, hyperspecialized residents faced strong pressures to perform robotic surgery on their patients, even when it was unclear whether robotic surgery was the best course of treatment. Patients demanded the robot because it was novel and ''high tech,'' and hospitals demanded that the robots get used to garner a reasonable return on their multi-million-dollar investment. These pressures and residents' success through shadow learning therefore contributed to the ongoing and highly controversial trend of performing robotic surgery on patients without strong evidence that it was superior to open surgery (Breeden, 2013; Liu et al., 2013).

**Consequences for shadow learners' cohort: Matthew effect for skill.** All residents in my study were required to participate extensively in open procedures, and APs routinely and fluidly granted them access to increasingly complex and risky opportunities to practice and meaningfully advance each procedure. Situated practice therefore had to be meaningfully granted in advance of the skill required to execute the work skillfully. The opposite was true with respect to robotic surgery: APs had no drive to involve residents in this work other than to give them an opportunity to practice, and the only way that residents gained meaningful access to such situated robotic practice was to demonstrate the skill required to execute the work without much coaching or intervention. If they did not do so—within moments of sitting down at the console—they were promptly publicly censured and/or ejected:

> So all right now it's time for the DVT [dorsal vein] stitch, go, do it. He steps off, you're on, then you run that play well and then you get to take the next snap [*referencing American football*]. That's how you get the maximum amount of time out of the console. Because it's limited, you know? We're only doing two or three cases a day, you know a couple times a week over those four months that's really not that much when you think about it. So if you screw up early on and you get kicked off the console, that's it. (Resident)

Those who engaged in shadow learning gained exclusive access to extensive collocated practice alongside an expert. This dynamic led to a self-reinforcing cycle in which those who engaged in shadow learning gained discrete, increasing, and disproportionate access to the best learning opportunities, while the opposite was true for ''average'' learners: ''Yeah, [in] our system high performers get more opportunities to do more, and by that become better, whereas the people who underperform probably get fewer opportunities, less time on the console, and they are sort of stuck in that rut'' (AP).

Thus as shadow learning became increasingly crucial to developing adequate robotic skill, the gap between credentials and actual skill widened for most trainees, as they could not participate sufficiently in the work. This Matthew effect and the hyperspecialization cited above exerted downward pressure on the already dwindling supply of skilled urologic robotic surgeons, just as demand for the technique was increasing (Dill and Salsberg, 2008; Decker et al., 2013; Fang et al., 2016).

**Consequences for shadow learners' community of practice: Limited learning.** Shadow learning was characterized by a culture of silence and plausible deniability, which limited the profession's ability to incorporate related practices into approved learning methods. On the one hand, shadow learning received no negative attention. Despite the fact that engaging in related practices clearly challenged norms and policy, I have no data that show residents facing consequences for engaging in them, and I have no data that show any AP (or other authority figure) enacting policy to explicitly prohibit them. Yet, on the other hand, shadow learning garnered very little positive attention: beyond APs occasionally making passing reference to somewhat analogous practices as instrumental to their learning, I have almost no data showing residents or APs sharing knowledge of these practices or suggesting them to each other, let alone indicating that they had personally relied on them. This was part of what allowed it to function—if everyone engaged in it, this star-pupil-take-all learning pathway would likely break down. But a lack of broader, more open discourse on the failures of legitimate peripheral participation and the effectiveness of shadow learning for robotic surgical technique essentially prevented the profession from learning—in this case adjusting the work and educational processes to keep pace with technological change to methods.

## DISCUSSION

By studying medical residents trying to learn robotic surgical technique, I found that trainees who successfully learn under these conditions do so via what I call shadow learning. If approved means are not sufficient, trainees who succeed must learn through practices that run counter to norms and/or policy and to which key stakeholders turn the proverbial blind eye. The learning literature does not explore this possibility. I turned to studies of norm-challenging practices for guidance. I found that shadow learning practices were frequently tolerated by key stakeholders, because they allowed for mutually desirable outcomes, even though they might have been punished or forbidden if viewed in the light of day. My theoretical contribution is to show how trainees learn skills core to a community of practice through such methods.

To date, we have studied learning in the light of day: collective, collocated, and consistently sequenced practices involving steadily increasing and somewhat risky involvement of trainees in experts' work, granted slightly in advance of requisite skill via a legitimized role. Learning in communities of practice has thus been theorized as occurring through legitimate peripheral participation (Lave and Wenger, 1991). In the open surgery I observed, trainees' learning proceeded according to current theory. Doing robotic surgery presented a set of conditions that prevented effective legitimate peripheral participation: trainees' errors were easy to perceive and hard to recover from, and trainees' participation was optional and constrained. I found that under these conditions, shadow learning was necessary for trainees to come to competence. Table 2 shows work characteristics conducive to legitimate peripheral participation versus shadow learning in this setting. Table 3 shows differences between the ways these processes were enacted, and figure 1 shows how shadow learning functioned in my setting.

### Shadow Learning in Other Contexts

Although their differences were valuable for highlighting shadow learning, robotic surgery and open surgery were also alike. Both required costly, lengthy training that built and relied on embodied skill and complex diagnostic frames. Both involved pronounced risk of catastrophic failure amidst significant uncertainty. Both were performed by a high-status occupation with ample resources. Both involved strong pressures to comply with and voice support for explicit, legitimized approaches to learning and training. Work such as aviation, diamond cutting, and bomb disposal often shares these similarities and displays the characteristics associated with robotic surgery in table 2, so we should expect shadow learning to arise there.

But to what extent are these community similarities and work characteristics required to block legitimate peripheral participation and thus drive shadow learning? The studies of butchery and midwifery cited at the beginning of this article suggest broadening our view. Both clearly showed legitimate peripheral participation breaking down, yet these communities of practice and the work they perform differ greatly from each other and those in my study. In butchery, putting master and apprentice in separate rooms made trainees' participation optional and delegation practically impossible. In midwifery, involvement and delegation were constrained by Western dictates, not by technological changes

**Table 2. Work Characteristics Conducive to Legitimate Peripheral Participation, Shadow Learning**

| Work characteristic | Legitimate peripheral participation (open surgery) | Shadow learning (robotic surgery) |
|---|---|---|
| Perceiving trainees' errors | *Harder/private:*<br>Only expert perceives trainees' errors, many are invisible (AP sees resident nick a small vein, then can't see him or her suture it in resulting pool of blood) | *Easier/public:*<br>Trainees' work is magnified and rebroadcast to all workers (resident nicks a capillary, causing a ''bleeder'' that appears ten times actual size on four TVs) |
| Recovering from trainees' errors | *Easy/concentrated:*<br>Expert can rapidly and personally deploy deeply practiced techniques to recover from trainees' errors<br>Risk peaks in middle of procedure (AP presses on a vein nicked by the resident, throws a stitch on it) | *Very hard/dispersed:*<br>Expert must initiate, direct, and wait for coordinated work to recover from trainees' errors<br>Risk peaks at beginning and end of procedure (AP waits for scrub to remove, clean, and reinsert camera, suck blood to expose a vein nicked by the resident, cauterizes it) |
| Involving trainees | *Extensive/necessary:*<br>Expert requires trainee help (AP retracts tissues and sucks fluids to allow resident to dissect tissues, sutures, cauterizes vessels) | *Restricted/optional:*<br>Expert does not require trainees' help (AP operates alone, briefly grants resident control to dissect simple, less vascular/nervous tissues) |
| Delegating to trainees | *Flexible/private:*<br>Expert regularly, easily, and quickly reallocates trainee's work across many dimensions to varying degrees<br>Delegating tasks and related feedback are largely tacit and private (resident struggles to dissect tissue, AP gently pushes it apart, allowing resident to clamp the target artery) | *Constrained/public:*<br>Expert rarely, easily, and quickly grants all-or-nothing control of the work to a trainee<br>Delegating tasks and related feedback are largely explicit and public (resident struggles to dissect tissues, AP loudly instructs resident, verbally notes errors, digitally takes complete control of robot, dissects out and clamps the target artery) |

to methods. But neither community could continue without some apprentices managing to learn in spite of these barriers, and norms for learning by legitimate peripheral participation were strong in both cases. This should encourage inquiry into shadow learning beyond communities and work defined by the conditions in this study.

Relatedly, it seems doubtful that figure 1 will fully describe shadow learning in all settings. Premature specialization, abstract rehearsal, and undersupervised struggle were roughly enacted in order in my setting, but this does not seem necessary in all cases. It does seem likely in many, however: to the extent that access to challenging work is predicated on demonstrations of fluid technique, many successful learners may engage in prior significant abstract rehearsal. Timing may also vary: my informants did not report engaging in these practices contiguously. In some cases they reported notable gaps in time between practices (e.g., between medical school and residency), and in others there were regular overlaps (e.g., many continued to engage in focused abstract rehearsal even as they were engaging in undersupervised struggle). Finally, I doubt I have identified the complete set of practices that constitute shadow learning in all settings. These were merely those clearly manifest in

**Table 3. Key Differences between Legitimate Peripheral Participation and Shadow Learning**

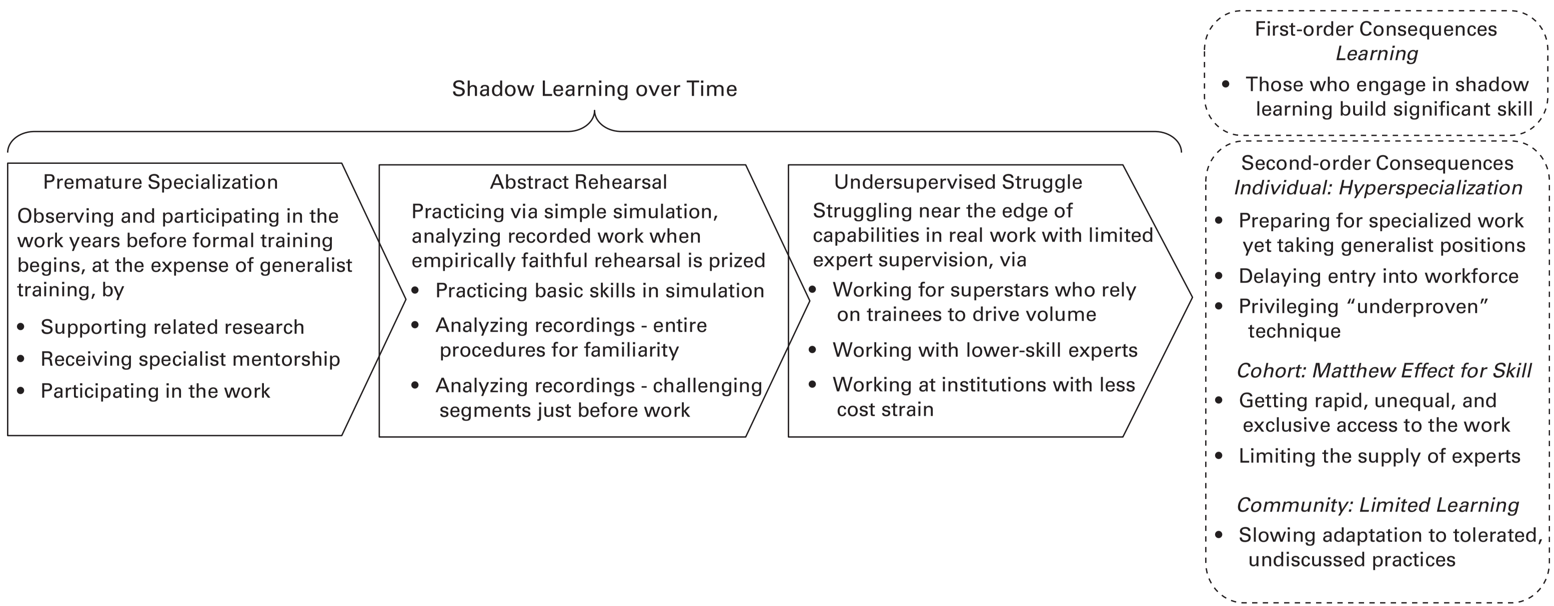
| Dimension of difference | Legitimate peripheral participation (open surgery) | Shadow learning (robotic surgery) |
|---|---|---|
| Relation to norms and policy for trainee learning | *Consistent:* Proceeds according to norms and policy (''see one, do one, teach one'' seen as right and proper, enshrined in residents' evolving role) | *Inconsistent:* Runs counter to norms and policy (improper educational sequence, abstract practice modalities, working without approved supervision levels) |
| Learning sequence | *Routinized:* Trainees engage habitually with a known, regular sequence of learning opportunities (residents ''see one'' first, ''do one'' later, ''teach one'' last) | *Opportunistic:* Trainees engage proactively with learning opportunities as they present themselves in daily practice (residents use the simulator in quiet times on night shift) |
| Community characteristics | *Collocated cohort:* Trainees develop skill together with extensive awareness of each other's pathways, drawing on local resources (residents learn, progress together) | *Distributed isolates:* Trainees develop skill on their own with very limited awareness of each other's pathways, drawing on nonlocal resources (residents learn alone, progress at other residents' expense) |
| Access to challenging work | *Access for competence:* Legitimized, necessary role grants trainees access to work near the edge of their capacity (residents deeply involved in almost every surgical move) | *Competence for access:* Skill from extensive norm- and policy-challenging practice grants trainees access to work near the edge of their capacity (residents gain access by showing robotic fluency) |

mine. The study of learning in very different communities of practice such as academic research, open source software, and government will likely reveal additional shadow learning dynamics, outcomes, and implications.

## Theoretical Implications

This study makes four theoretical contributions beyond introducing shadow learning. First, it connects situated and cognitive theories of learning in organizations. Lave and Wenger (1991) showed that treating learning as occurring *only* in individual minds and resulting in skills and knowledge possessed by individuals missed that such learning occurs as part of and through an embedded or situated social context. Studies of situated learning have since focused on these more social and embedded processes and aspects of learning, likely in an effort to explore learning beyond prior individual, cognitive models. We seem to have lost sight of Lave and Wenger's original, more holistic thesis as a result. By examining an opportunistic and isolated form of learning that nonetheless produced outcomes critical to sustaining a community of practice, this study shines a light on an empirical context in which learning more obviously involved both situated and cognitive components. Attending to both promises the analytic flexibility that my empirical context encouraged: we are more likely to inquire into individuals and skills as well as practices and settings to the extent they matter for learning. This seems particularly important as individuals and skills have become increasingly mobile and distributed in a growing gig economy (Barley and Kunda, 2006; O'Mahony and Bechky, 2006).

**Figure 1. Shadow learning for acquisition of robotic surgical skill.***




* Chevrons intersect to indicate practices occasionally overlapped in time.

Second, in an age in which power-law-type distributions of talent are increasingly evident (Rosen, 1981; Brown, 2011), this study raises important questions about the distribution of learning gains among a cohort of trainees. Prior studies have not focused on whether and how different trainees may learn at different rates and the implications of an individual's learning for that of their compatriots'. This may well be because studies that draw on legitimate peripheral participation show or presume equifinality: once granted legitimate access, all trainees get equal opportunity to participate in the work, and for the work's sake, experts must flex this opportunity in many ways to help all learners get what they need as they go. Additionally, trainees and experts share stories and experiences (Orr, 1996), and this communal tide raises all learners' boats. My study offers a stark contrast—much of the successful residents' shadow learning occurred years before they set foot in an OR during their residency, these advantageous practices were not discussed or formalized in their cohort, and as a result these successful learners were rapidly granted disproportionate access to work opportunities just as their peers were rapidly deprived of them.

Third, the empirical patterns and findings from this study contrast with current conceptions of a community of practice, suggesting that a finer-grained conceptualization is in order. As they were doing and learning open surgery, the residents and APs in my study maintained good working relationships with each other, worked side by side when feasible, progressed together, and openly exchanged knowledge about their practice. They *looked* like the communities of practice we see in the literature: communal, connected, and collocated (Brown and Duguid, 1991; Orr, 1996). In shadow learning this kind of community faded—residents often learned in isolation and did not communicate regularly or publicly with their local cohort and mentors about how they were managing to learn. Yet through abstract rehearsal, these shadow learners shifted toward a broader digital community of surgery and surgeons that was dispersed in space and time: experts recorded procedures and uploaded them to the Internet, and apprentices watched them anonymously, miles and sometimes years away. Where, conceptually, does a community of practice begin and end in our increasingly distributed, digital, and dynamic world? A clearer answer to this question could help us understand how such communities function and where they are headed.

Fourth, this study shows that well-intended experts may inhibit trainees' learning through their attempts to facilitate it. Prior research has shown experts and higher-status individuals facilitating learning as they adopt participative and encouraging interaction styles, and it has shown that learning fails when experts fail to help appropriately (Edmondson, Bohmer, and Pisano, 2001; Bunderson and Reagans, 2011). By illuminating the dynamics of helicopter teaching, this study shows how higher-status actors can do this to excess and so block learning. This outcome is most likely to occur when—as was the case with robotic surgery—it is easy for experts to see trainees' errors, difficult for experts to remediate them, and easy for experts to take control of the work. I show that lower-status actors may need to engage in shadow learning to earn leeway from these experts who would otherwise be compelled to "help" (Perlow and Weeks, 2002).

## Implications

First, this study raises important questions about the supply of skilled professionals as technologies make it possible for masters to perform work with less assistance. My study offers strong evidence that efficiency and liability pressures may win the day at the expense of maintaining legitimate peripheral participation in skilled work: the da Vinci system allowed surgeons to share simultaneous control of the robot with trainees, but I never observed this, my informants said they never saw it, and salespeople from Intuitive Surgical told me the practice was exceptionally rare. This turn toward expert control comes at the expense of trainees' involvement. This and related dynamics outlined in this paper may contribute to shifting talent away from normal-type distributions toward those that more resemble power-law-type distributions. Yet as in aviation, abstract rehearsal may become an increasingly accepted mode of acquiring basic competence with novel technology-dependent methods, allowing a wider range of trainees to more than make up for lost time learning on the job, expanding and enriching the talent pool. Such questions clearly warrant subsequent study.

Second, this study raises important questions about the costs and benefits associated with superstar-type markets for talent, especially as shadow learning becomes more salient. On the one hand, those residents who made exceptional progress through shadow learning did so to some degree at the expense of their fellow "average" students' learning and on the backs of patients, experts, and institutions who could least afford to insist on higher quality standards. And hyperspecialization meant that shadow learners were underprepared for the generalist jobs that most of them would occupy. Catastrophic failure and lawsuits may be more common in such circumstances, and those consumers and institutions who can pay the most may face these risks far less frequently. Such dynamics raise serious questions of equity, especially in communities that stake their legitimacy on upholding this core value. On the other hand, it was also clear that residents who succeeded through shadow learning may have minimized risk to patients in situations in which the AP had less robotic skill than they did. Thus shadow learning may actually ensure quality for the consumers and institutions who can least afford to insist on it. These compelling questions should be addressed in subsequent study.

Finally, in a world of work characterized by technologies that allow experts to work with less trainee help, shadow learning may play an increasingly central role in trainees' progression to skill. This would have far-reaching implications. If lawyers, electricians, pilots, accountants, filmmakers, clergy, and police officers in training need to engage in increasingly premature specialization, abstract rehearsal, and undersupervised struggle, successful members of these professions may increasingly treat rules and norms as optional reading; learning as an opportunistic, isolated experience directed by the trainee; cohort members as competing against each other; and access to the work as a privilege granted to a small trainee minority. These and other professions have heretofore built knowledge, added value, and extended jurisdiction through roughly the opposite orientation. Consequences for skilled labor may mirror those outlined in this study—a small and shrinking hyperspecialized minority that cannot possibly serve the needs of a broader population, a majority that is losing the skill to do the work effectively, and communities of practice that don't know what they don't know about how learning is actually occurring on the ground.

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## ORCID iD

Matthew Beane https://orcid.org/0000-0002-1961-4585

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## Author's Biography

**Matthew Beane** is a project scientist at the Technology Management Program at the University of California, Santa Barbara, 1316 Phelps Hall, Santa Barbara, CA 93106 (e-mail: mattbeane@tmp.ucsb.edu). His research uses ethnographic methods to study deviance in work involving machine intelligence and robotics. He earned a Ph.D. in management from the Information Technologies Group at the MIT Sloan School of Management.