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Meeting the mathematical demands of the safety-critical workplace: medication dosage calculation problem-solving for nursing

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Abstract This article addresses a key issue for mathematics educators preparing students for work: How should teaching, learning and assessment be designed to meet the mathematical demands of the workplace, especially when those demands are safety-critical? We explore this question through a discussion of our interdisciplinary research on numeracy for nursing, focusing in particular on the characterization and authentic assessment of competence in medication dosage calculation problem-solving, where errors can and do cause patient morbidity and mortality.

Keywords Numeracy · Nursing · Medication dosage calculation problem-solving · Drug errors, teaching · Learning · Assessment · Authentic

1 Introduction

Our focus in this article is on a key issue for vocational mathematics educators: how should teaching, learning and assessment be designed to meet the mathematical demands of the workplace, especially when those demands are safety-critical, as in nursing? In exploring this issue, we draw on a programme of medication dosage calculation problem-solving (MDC-PS) education research that has evolved over a 20-year period since 1992. We have chosen to focus on MDC-PS because it is a high risk and high profile area of vocational mathematics for nursing. The research was undertaken by two interdisciplinary international research teams whose collective work is reported in an eight-paper series, "Safety in Numbers", in the journal *Nurse Education in Practice* (see Weeks, Sabin, Pontin, & Woolley, 2013, for a summary of this work).

Our premise in this article is that vocational mathematics education should prepare our twenty-first-century students and workforce to be competent in solving real-world mathematical problems, particularly in safety-critical contexts such as nursing. We argue that this

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requires the close alignment of authentic teaching, learning and assessment activities to bridge the gap between theory and practice, and between knowledge and performance. For a highly regulated practice-based profession such as nursing, the achievement of this alignment requires a uniform understanding and application of agreed benchmarks and taxonomies of knowledge and skills. This requires the profession's regulator, education establishments, clinical mentors, assessors and students to collectively agree, understand and apply the form and content of a benchmark and taxonomy. There is currently no agreed benchmark setting out the vocational mathematics required for nursing education and professional practice in the UK (or elsewhere). However, as described below, recent innovative work reported in the "Safety in Numbers" series has informed a UK regulatory framework within which a benchmark, yet to be agreed by the profession, can be articulated. We contend that such a benchmark is essential to inform measures designed to ensure safe and effective nursing practice.

Within this context, we focus on the development and assessment of the vocational skills, knowledge and understanding required to minimize preventable errors by nurses in prescribing, dispensing, calculating dosages, preparing or administering drugs.[1] Such errors can have tragic consequences for both the patient and the health-care professional. Incidents are regularly reported in the press, for example: "Mother-of-four dies after blundering nurse administers TEN times drug overdose" (Daily Mail Reporter, 2011), and in a recent case, the suicide of a health-care professional was reported: "Nurse's suicide highlights twin tragedies of medical errors" (Aleccia, 2011). However, it is rare that headlines such as these are balanced with press reports of the significant and innovative work being undertaken in the health professional education and clinical fields to address this international problem. This is exemplified by a growing number of studies, both of qualified nurses—for example, Grandell-Niemi, Hupli, Leino-Kilpi, and Puukka (2003) in Finland and Hoyles, Noss, and Pozzi (2001) in the UK—and of nursing students—for example, in the USA (Rainboth & De Masi, 2006), the UK (Coben, Hall, Hutton, Rowe, Weeks, & Woolley, 2010; Jukes & Gilchrist, 2006) and Australia (Eastwood, Boyle, Williams, & Fairhall, 2011).

The jury is still out on the part played by nurses' numeracy skills in errors in prescribing, dispensing, calculating, preparing or administering drugs. Indeed, a recent review found insufficient evidence to suggest that medication errors are caused by nurses' poor calculation skills, although the author concluded that more research is required into calculation errors in practice (Wright, 2010). We believe that calculation skills are only part of the picture, as shown in the definition of numeracy and the model of competence in MDC-PS set out below. We developed the model as members of one of the two research teams contributing to this collaborative work: the NHS (National Health Service) Education for Scotland (NES) inter-disciplinary Expert Numeracy Reference Group (hereinafter: the Reference Group), building on earlier work outlined below. The Reference Group undertook research on the *Benchmark assessment of numeracy for nursing*: *Medication dosage calculation at point of registration* project commissioned by NES (Coben et al., 2010).

The outcomes of the NES research programme were reported to the UK nursing regulatory body, the Nursing and Midwifery Council (NMC) in 2010. These outcomes subsequently part-informed the construct and content of the MDC-PS competence rubric within the NMC's Essential Skills Cluster (ESC) for Medicines Management (NMC, 2010a) (see Table 1).

In addition, drawing on the NES research, the NMC's *Advice and Supporting Information for Implementing NMC Standards for Pre-Registration Nursing Education* states that

[1] Adverse drug events (ADEs) are characterized by Bates et al. (1995, p. 29) as "an injury resulting from medical intervention related to a drug".

Table 1 MDC-PS competencies within the NMC ESC for medicines management (NMC, 2010a)

Essential skills cluster: medicines management (1)

The newly qualified graduate nurse should demonstrate the following skills and behaviours. They should be used to develop learning outcomes for each progression point and for outcomes to be achieved before entering the register.

33 People can trust the newly registered graduate nurse to correctly and safely undertake medicine (2) calculations.

First progression point	Second progression point	Entry to the register	Indicative content
1 Is competent in basic medicine calculations (*) relating to:		2 Is competent in the process of medication-related calculation in nursing field involving:	Numeracy skills, drug calculations required to administer medicines safely via appropriate routes including specific requirements for children and other groups.
• Tablets and capsules		• Tablets and capsules	
• Liquid medicines		• Liquid medicines	
• Injections including:		• Injections	
		• IV infusions including:	
• Unit dose		• Unit dose	
• Sub- and multiple-unit dose		• Sub- and multiple-unit dose	
• SI unit conversion		• Complex calculations	
		• SI unit conversion	

Programme providers may wish to take the following information into account when determining assessment criteria:

1. An ESC assessment strategy for medication-related calculation that demonstrates competency across the full range of complexity, the different delivery modes and technical measurement issues.
2. Assessment that takes place in a combination of the practice setting, computer lab and simulated practice that authentically reflects the context and field of practice.
3. Diagnostic assessment that focuses on the full range of complexity, identified at each stage, and recognizing the different types of error (conceptual, calculation, technical measurement), which can then be linked to support strategies.

(NMC, 2010b, pp. 61–62)

Although the NMC statement falls short of directly *advising* programme providers to take the information into account when determining assessment criteria, nevertheless, this is an important step towards the adoption in the UK of a more comprehensive, evidence-based approach to the development and assessment of professional competence in numeracy for nursing. Hutton subsequently developed a unified nursing numeracy taxonomy, which mapped to the 42 NMC ESCs extant from 2010 (Young, Weeks, & Hutton, 2013). In further advancing this body of work, in this article we aim to do the following:

- Explore the development of professional competence in nursing
- Consider the conceptualization and definition of numeracy and evidence-based criteria for the assessment of numeracy in nursing

- Review the problem of articulating MDC-PS competence in a word-based form and the need to facilitate the "learning to see" and uniform understanding of essential regulatory MDC-PS requirements
- Propose a model that reflects the integration of three competence sub-domains of MDC-PS that need to be manifested by the registered nurse in clinical practice
- Illustrate the essential design features of an authentic virtual learning and diagnostic assessment environment, based on the principles of alignment of authentic teaching, learning and assessment and bridging of both the theory-practice and knowledge-performance gaps, and
- Discuss some implications of our analysis for vocational mathematics education beyond nursing

2 The development of professional competence in nursing

The *raison d'être* of professional nursing education programmes is to facilitate the development of practitioners who demonstrate professional competence in the following domains: cognitive competence (*knowing that* and *knowing why*); functional competence (*knowing how* and *skills*); ethical competence (the embodiment of a professional value system); and personal competence (the ability to apply these competences in different practice situations) (Commission of the European Communities, 2005; Weeks, Hutton, Coben, Clochesy, & Pontin, 2013a). However, the traditional organization of nursing (and most other) vocational education systems has typically perpetuated a distinction between the teaching and assessment of knowledge and the teaching and assessment of professional practice skills and values.

These systems have, in turn, created an artificial theory-practice gap and an artificial knowledge-performance gap that has largely separated the teaching and learning of the professional body of knowledge from the teaching and learning of professional know-how and skilled performance (Lum, 2009; Weeks et al., 2013a). This problem is complicated by the common practice of articulating competence and assessment problems in an abstract and descriptive word-based form and then requiring the interpretation, transfer and measurement of such competence statements in authentic practice environments. When the professional know-how and skilled performance involves mathematics, as in MDC-PS, the problem is further exacerbated by several factors. These include the tendency for mathematical processes to become invisible in the workplace: "crystallised in 'black boxes' shaped by workplace cultures" as Williams and Wake (2007, p. 317) put it. Problems in the transfer of learning, defined as the ability to apply what has been learned in one context to new contexts (Byrnes, 1996, p. 74), are another exacerbating factor. Transfer of learning between the classroom and the workplace does not happen automatically, as Eraut (2004) and others (e.g. Evans, 2000; FitzSimons & Wedege, 2007) have shown. In addition, the incoherent nursing numeracy assessment regime and invalid test items applied in high-stakes testing found by Coben, Hodgen, Hutton and Ogston-Tuck (2009) in one large school of nursing in England may be indicative of a wider problem in nursing education. Such assessment regimes commonly include word problems in an attempt to contextualize assessment, but the limitations of word problems in mathematics education are well attested (e.g. Brown, Collins, & Duguid, 1989; Hoogland, Bakker, De Koning, & Gravemeijer, 2012; Verschaffel, Greer, & de Corte, 2000). We argue that when professional practice is safety-critical, as in MDC-PS, any disjuncture between theory and practice and between knowledge and performance may have serious consequences.

2.1 Conceptualization of numeracy for nursing

The term *numeracy* is commonly used in nursing to denote the mathematical demands of professional nursing practice, and the Reference Group was mindful of the terminological confusion and contestation around the term (Coben et al., 2003). After FitzSimons and Coben (2009), we consider the construct of numeracy to be best understood as an example of what Bernstein calls a horizontal discourse: one in which knowledge is "embedded in on-going practices, usually with strong affective loading, and directed towards specific, immediate goals, highly relevant to the acquirer in the context of his/her life" by contrast to the vertical discourse of mathematics (Bernstein, 2000, p.159). Against this background, the Reference Group adopted the following generic definition:

> To be numerate means to be competent, confident, and comfortable with one's judgments on *whether* to use mathematics in a particular situation and if so, *what* mathematics to use, *how* to do it, *what degree of accuracy* is appropriate, and *what the answer means* in relation to the context. (Coben, 2000, p.35, emphasis in the original)

This definition was chosen because it characterizes numeracy as the exercise of judgment with respect to specific issues in relation to the demands and affordances of a given context; in this case, nursing. It allowed us to explore issues of competence in MDC-PS and to delineate what we did and did not consider to be numeracy issues in that context. Our formulation of the relationship between the domains involved in our analysis (numeracy, health-care numeracy, medicines management and medication dosage calculation) is given below (Fig. 1).

2.2 Evidence-based criteria for the assessment of numeracy for nursing

In working towards the establishment of evidence-based criteria for the assessment of numeracy for nursing, the Reference Group adopted Gulikers, Bastiaens, and Kirschner's (2004, pp. 71–75) framework of five dimensions that inform the design and articulation of assessment environments. The issue of what *authenticity* means in this context is discussed below. We summarize Gulikers et al.'s framework as follows:

1. *Task*: Students should be exposed to authentic tasks that involve integration of knowledge, skills and attitudes. The tasks should be meaningful and relevant to the student and should

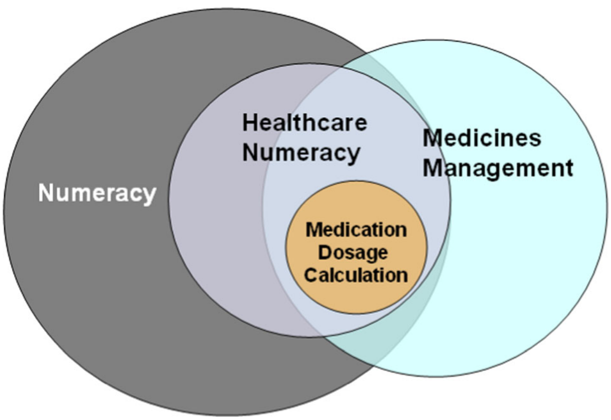


Fig. 1 Medication dosage calculation in the context of numeracy and medicines management (Coben et al., 2010, p. 13)

reflect the full range of complexity, domains of practice and structure of the tasks as encountered in the real practice setting.

2. *Physical context*: The tasks should be learned and assessed in physical contexts that are as congruous as possible with the real physical practice setting and should be undertaken and assessed using the typical tools available in the setting and along similar time frames available to undertake the real tasks.
3. *Social context*: The social context of the practice setting should be as closely aligned as possible in respect of the individual or groups of professionals typically engaged in problem-solving and undertaking the tasks.
4. *Criteria*: Assessments should be centred on criterion-referenced outcomes, should be based on the criteria used in professional practice and should be realistic and transparent in respect of the processes and outcomes expected in the practice setting.
5. *Form/result*: Competence should be demonstrated and measured in respect of professionally relevant results that are observable and subject to multiple indicators of learning.

The framework was employed for evaluating the authenticity and construct validity of a proposed benchmark assessment tool and associated assessment environment for MDC-PS in higher education institution and practice settings. The Reference Group focused on the task, physical context and social context design features of authentic assessment environments, with student performance data measured against the criteria and form/result dimensions. The framework was also used to evaluate nursing students' perceptions of congruence between the authentic assessment environment and medication dosage problem-solving and computation requirements in practice settings (Coben et al., 2010).

Based on a critical review of relevant literature (Sabin, 2001), evidence-based criteria for the assessment of numeracy for nursing were proposed by the Reference Group aligned with Gulikers et al.'s (2004) framework.[2] On this basis, the Reference Group determined that such assessment should be as follows:

> *Realistic*: Evidence-based literature in the field of nursing numeracy (Hutton, 1997; Weeks, Lyne, Moseley, & Torrance, 2001) strongly supports a realistic approach to the teaching and learning of calculation skills, which in turn deserve to be tested in an authentic environment. Questions should be derived from authentic settings. A computer based programme of simulated practice in drug calculations, formative testing, with feedback on the nature of errors made, has been shown to develop competence in medication dosage calculation (Weeks, Lyne, & Torrance, 2000). Exposure of students to real-world situations is recommended (Weeks, 2001).
> *Appropriate*: The assessment tool should determine competence in the key elements of the required competence (Sabin, 2001; OECD, 2005).
> *Differentiated*: There should be an element of differentiation between the requirements for each of the branches and fields of nursing (Hutton, 1997).
> *Consistent with adult numeracy principles*: The assessment should be consistent with the principles of adult numeracy learning teaching and assessment, having an enablement focus (Coben, 2000).
> *Diagnostic*: The assessment tool should provide a diagnostic element, identifying which area of competence has been achieved, and which requires further intervention

[2] Work by the Reference Group towards the establishment of evidence-based criteria for the assessment of numeracy for nursing is summarized more fully in Coben et al. (2008).

(Black & Wiliam, 1998). Thus it should "provide information to be used by students and teachers that is used to modify the teaching and learning activities in which they are engaged in order better to meet student needs. In other words, assessment is used to 'keep learning on track'" (Wiliam, 2006).

Transparent: The assessment should be able to demonstrate a clear relationship between 'test' achievement and performance in the practice context (Weeks et al., 2001).

Well-structured: The tool should provide the following:

- A unique set of questions with a consistent level of difficulty.
- A structured range of complexity.
- The assessment should take place within a defined framework, at points by which students can be effectively prepared, while allowing time for supportive remediation. (Hodgen & Wiliam, 2006)

Easy to administer: The assessment should provide the opportunity for rapid collation of results, error determination, diagnosis and feedback (Black & Wiliam, 1998).

(Coben et al., 2008, pp. 96–97)

Having proposed these evidence-based criteria for the assessment of numeracy for nursing, the Reference Group moved on to address the problem of articulating MDC-PS competence in a word-based form. This work is outlined in the following section.

3 The problem of articulating MDC-PS competence in a word-based form

Word-based competence rubrics (such as that shown in Table 1), statements and regulatory body advice are common features of traditional competence-based professional education and training programmes, based on the assumption that competence can be described and communicated through language in accurate and unequivocal terms. However, this has been challenged by Lum (2009), who points to "profound and irrevocable difficulties with the idea that competence can be specified in clear and precise terms" (p. 76). This difficulty in accurately defining and describing particularly functional competence (know-how and skilled performance) in a word-based form results in the potential for variable interpretation of the required competence in vocational and practice-based professions like nursing. For example, without a shared and uniform understanding of terms such as *conceptual competence*, *calculation competence*, or *technical measurement competence*, or *unit dose* and *sub- and multiple-unit dose calculations* and so forth, as in the NMC descriptors of competence in MDC-PS shown in Table 1, misinterpretation or variable interpretation by educators and students can (and does) occur. To counter this problem within the MDC-PS competence domain (and other vocational mathematics domains), we have proposed that both *knowing that* and authentic virtual *knowing how* representations of MDC-PS competence can be additionally modelled in an *iconic mode of representation* (Bruner, 1975), to illustrate the fundamental principles of how competent MDC-PS should be manifested and assessed in authentic practice environments. We turn next to consider what is meant by authentic assessment in this context and present our work on the modelling and measurement of MDC-PS competence in virtual and practice-based environments.

4 Authentic assessment and modelling and measurement of MDC-PS competence in virtual and practice-based environments

Authenticity in assessment has been investigated in the mathematics education literature (e.g., Bonotto, 2009; Frankenstein, 2009; Lave, 1992; Morgan, 2003; Zevenbergen & Zevenbergen, 2009) although, as Morgan (2003, p. 37) has pointed out, the term authentic has often been used as if it were unambiguous. Authenticity has also featured in the discourse of reform in the mathematics education of children, strongly influenced in the USA by the National Council of Teachers of Mathematics (NCTM) (Morgan, 2003, p. 38). In the field of education more generally, researchers Cumming and Maxwell (1999) argue that "contextualisation of authentic assessment within the teaching, learning and assessment domain is where future effort should be directed" (p. 15). Our work described here attempts to answer this call with respect to the assessment of MDC-PS, a key aspect of numeracy for nursing.

Mueller (2005) defined authentic assessment as "a form of assessment in which students are asked to perform real-world tasks that demonstrate meaningful application of essential knowledge and skills" (p. 2). In the nursing education context, if we are to bridge the gaps between theory and practice and between knowledge and performance effectively, it is necessary to design and employ authentic teaching and assessment environments that facilitate the seamless, integrated and dovetailed learning of cognitive competence (*knowing that* and *knowing why*) with learning of the functional competence (*knowing how* and skills) requirements of the practice setting. The solution to this conundrum may be found through combined and phased learning and assessment undertaken in two forms.

The first is a safe and controlled authentic virtual environment populated with both interactive iconic representations of real MDC-PS functional objects found in practice settings, and the analogous professional language and mathematical symbols used to describe them. Within the virtual environment authentic assessments are designed to (a) test the validity of a student's schemata (internal cognitive representations of the MDC-PS process); (b) test cognitive competence in MDC-PS; and (c) enculture and sensitize the student to the functional competence requirements of the practice setting. They are also designed to be truly representative of performance in the field and align to assessment criteria that seek to evaluate essentials of performance against well-articulated performance standards.

The second is a practice-based environment where cognitive, functional, ethical and personal competence in MDC-PS can be integrated and evaluated under field conditions. A commitment to authenticity thus requires a recognition of the contingencies of real-world nursing practice, encompassing situations where "knowledge is limited, time is pressing, and deep thought is often an unattainable luxury" (Todd & Gigerenzer, 2000, p. 727).

Bridging of the theory-practice and knowledge-performance gaps is critical in the domain of MDC-PS and other vocational mathematics domains where assessment schedules must reliably and validly measure the construction, synthesis and meaningful application of the mathematical and measurement knowledge, problem-solving and professional skills that underpin safe and effective professional practice. Thus, the hallmark of authentic assessment environments is their capacity to measure the meaningful application of cognitive competence (knowledge) and functional competence (know-how and skills) in realistic contexts, together with the provision of a rubric (diagnostic framework) against which to measure performance (Sabin, Weeks, Rowe, Hutton, Coben, & Hall., 2013). Above all, "within reasonable and reachable limits, a real test replicates the authentic intellectual challenges facing a person in the field" (Wiggins, 2011, p. 84).

In the light of these considerations, and because it relates well to the adult and professional education focus of our study, the Reference Group adopted Gulikers et al. (2004) definition of authentic assessment as follows:

> an assessment requiring students to use the same competencies, or combinations of knowledge, skills, and attitudes, that they need to apply in the criterion situation in professional life. The level of authenticity of an assessment is thus defined by its degree of resemblance to the criterion situation. (p. 69)

For the purposes of extrapolating and operationalizing a definition of dosage calculation competence based on the above definition of numeracy and maintaining consistency with the criteria for the assessment of numeracy for nursing set out above, the Reference Group adapted a competence model derived from an initial premise described by Weeks et al. (2000), and elaborated by Authentic World Ltd.[3] Figure 2 illustrates a competence model that provides generic definitions for the three sub-elements of MDC-PS competence (conceptual, calculation, technical measurement). Figure 3 illustrates an analogous competence model that reflects an exemplar computer-generated iconic representation of the requirements for solving a unit dose injection-based dosage calculation problem. Comparison of these two models highlights the difficulty, noted by Lum (2009) above, in accurately describing competence in precise detail in a word-based form. It also shows how analogous computerized iconic modelling adds essential pictorial detail for the student when both constructing schemata (internal cognitive representations of an individual's world) and learning competent MDC-PS practice, also for the educator and clinician when assessing competence requirements against a defined rubric (see, e.g., Table 1).

Figures 2 and 3 articulate the interrelationship between the three sub-elements that combine to form competence in MDC-PS. The intersection of the model (the central white section shown in Fig. 2) highlights how all three sub-elements must be practised concomitantly in order to achieve a correct dosage or rate solution. Conversely, an undiagnosed and uncorrected error in one or more of the three sub-elements of the competence model *will* result in a medication dosage calculation error in clinical nursing practice. Consequently, we argue that it is imperative that nursing students are supported in the development of schemata and competence in MDC-PS and undertake systematic diagnosis of cognitive and functional competence in authentic assessment and clinical practice environments (Sabin et al., 2013; Weeks et al., 2013). Next, we provide a short summary of the central theoretical perspectives that informed the design of an online diagnostic teaching, learning and assessment environment designed to meet this imperative.

5 The essential design features of an authentic virtual learning and diagnostic assessment environment

The design of the *safeMedicate*[4] virtual environment is underpinned by a constructivist and situated cognition perspective that actively engages learners in knowledge construction through their active engagement with the context-bound functional objects (artefacts), language, symbols and tools of the social and clinical environments within which the professional knowledge is to be applied. These evolving perspectives, together with the articulating

[3] http://www.authenticworld.co.uk/

[4] *safeMedicate* is ©Authentic World Ltd.

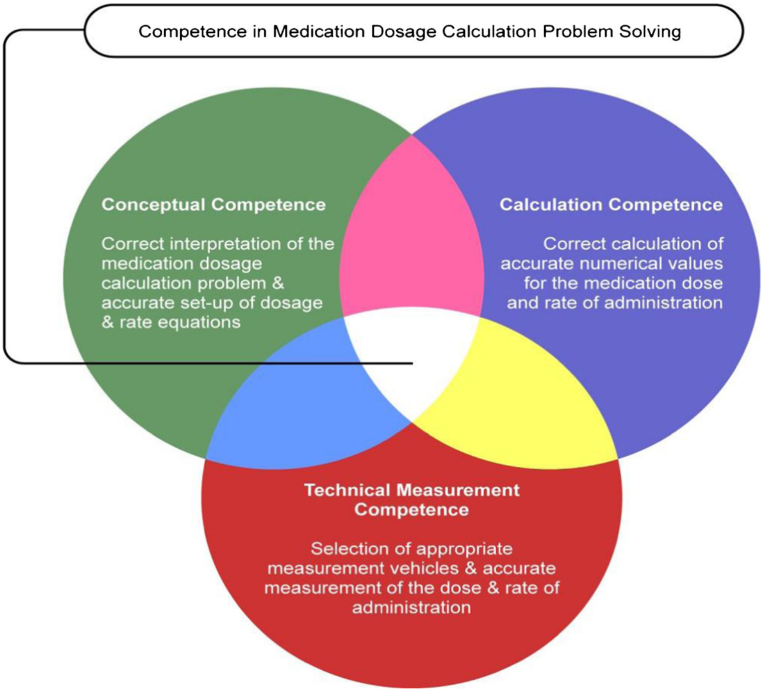


Fig. 2 MDC-PS competence model (generic word-based definitions)

cognitive apprenticeship, cognitive style in mathematics and non-threatening features of the learning and assessment environments, have informed the design of these online programs. This process is fully explored by Weeks, Hutton, Coben, Clochesy, and Pontin (2013b).

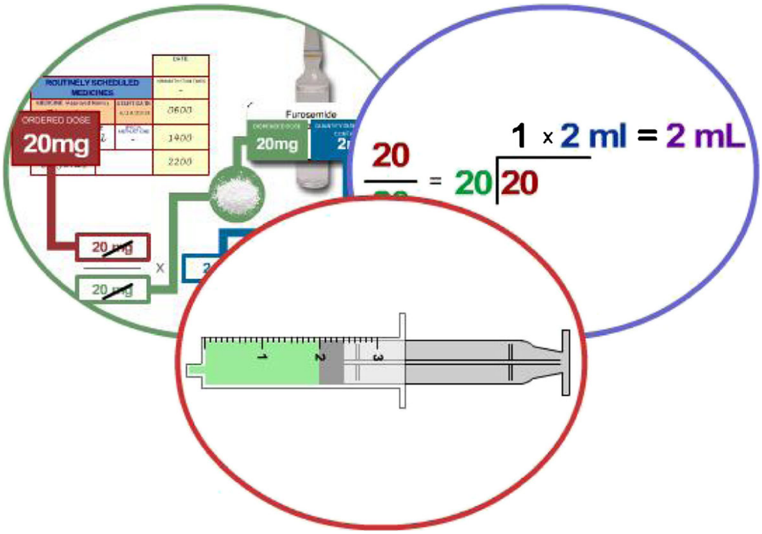


Fig. 3 MDC-PS competence model (example of iconic representations for a "unit dose" injection-based dosage calculation problem)

This approach lies in stark contrast to traditional didactic transmission methods of vocational mathematics education in nursing education that not only fail to engage the learner actively in knowledge construction, but also largely rely on the use of abstract word problems to describe the clinical and social features of medication dosage calculation (MDC) problems and to assess cognitive competence. Figure 4 illustrates a typical word-based essential skills MDC problem in this genre.

Word problems of this type are highly stylized and formalized, unlike "inherently ambiguous and open-ended" authentic challenges (Wiggins, 2011, p. 85). They inform the learner of the prescribed dose and the dispensed dose and so forth—a luxury not afforded to the registered nurse in clinical practice. In reality, as illustrated in our competence model (Figs. 2 and 3) the competent registered nurse is required (a) to understand conceptually and to interpret this numerical information from prescription charts and medication ampoule labels, and so on (b) to calculate an accurate numerical value for the dose and (c) to perform an accurate technical measurement of the dose in an appropriately selected measurement vehicle (in this case a syringe of an appropriate design and volume). By contrast, Fig. 5 illustrates an example from an authentic diagnostic assessment environment that represents the same MDC problem as that described in words in Fig. 4. The example illustrates the presentation of the problem in an authentic iconic form, within which the medication language and dosage symbolization typical of the real-world practice setting are embedded; together with diagnostic feedback on problem-solving performance relevant to conceptual competence, calculation competence and technical measurement competence. Macdonald, Weeks, and Moseley (2013) further informed this premise and illustrated examples of competence assessment for unit dose, multiple-unit dose, sub-unit dose and conversion of SI unit MDC-PS calculations. Note that the images in Fig. 5 are screenshots and do not show the dynamic nature of the assessment, whereby students select appropriate dose measurement vehicles, drag and drop tablet icons into containers, draw up liquid medicine into a syringe and set intravenous infusion pump and drop rates. Our research, in which nursing students' performance in this dynamic iconic computerized environment was compared with their performance on the same tasks in a simulated practice environment (Coben et al., 2010), has shown that these models provide exemplar benchmarks for competent performance, meeting the requirements of the NMC ESC hierarchical rubric illustrated in Table 1.

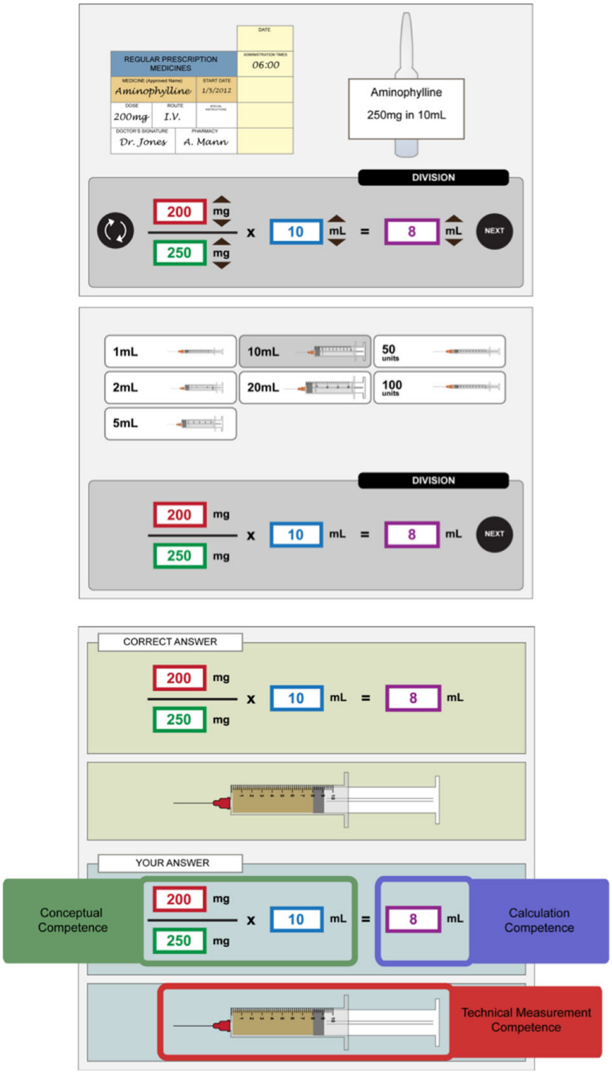
Macdonald et al. (2013) evaluated the effectiveness of the *safeMedicate* program, tracking the progress of 210 pre-registration nursing students' MDC-PS competence development over 3 years. Although many students displayed a range of arithmetical deficits on entry to the undergraduate programme, exposure to the authentic virtual environment and practice-based learning environments facilitated all participants' demonstration of MDC-PS cognitive competence (*knowing that* and *knowing why*), demonstrated by scoring 100 % in the field-specific Authentic Diagnostic Assessment (ADA) element of the authentic virtual environment; and MDC-PS functional competence (know-how and skills), demonstrated by successful completion of all NMC medicines management and MDC-PS competencies in practice-based competency assessments.

On the basis of this and other research summarized by Weeks, Sabin et al. (2013); Weeks, Higginson, Clochesy, and Coben (2013) have explored a grounded theory of schemata and

Prescribed dose, Aminophylline 200 mg,
Dispensed dose, Aminophylline 250 mg / 10 ml.
What volume should be drawn up for injection?

Fig. 4 A typical word problem used to assess medication dosage calculation problem-solving ability

Fig. 5 Computerized iconic model illustrating conceptual, calculation and technical measurement cognitive competence diagnostic feedback for a typical essential skills "complex dose" injection calculation



competence construction for MDC-PS. Within this grounded theory, we stress the importance of the student *seeing* and actively engaging with medication dosage functional objects and their iconic representations, within which essential numerical and measurement information is embedded (e.g., prescription charts, medication ampoule labelling, syringes, etc.). Our research suggests that this, rather than working through word-based dosage problems, better supports the construction of accurate schemata for, and the development of, nursing students' competence in MDC-PS.

Learning to *see* the vocationally relevant features of the world may be particularly important. Lum (2009) notes that

> a considerable part of what it is to be vocationally capable consists in being able to apply schemata which enable us to 'see' those features of the world which are relevant and perhaps even unique to a particular vocational role. (p. 102)

The importance of seeing numeracy problems was evident in Hoogland et al.'s (2012) randomized controlled trial: students scored significantly higher on image-rich numeracy problems than on comparable word problems. The dynamic online learning environment facilitates *seeing plus*: seeing in the context of engagement with a comprehensive range of vocationally appropriate virtual artefacts in the process of solving a range of MDC problems in a safe, controlled environment that is accessible at any time. This is important in safety-critical work such as nursing.

6 Implications for vocational mathematics education beyond nursing

We believe our work offers a model for vocational mathematics education, which may be critiqued and developed in other vocational contexts. It adds to knowledge and understanding of a key aspect of numeracy (MDC-PS) for the safety-critical context of nursing, exemplifying and adding to the evidence base on the importance of authentic assessment, supported by authentic pedagogies, in vocational mathematics education. Other safety-critical vocational contexts with a strong mathematical component include aviation and finance (Bakker, Hoyles, Kent, & Noss, 2006; Noss, Hoyles, & Pozzi, 2000); and the chemical industries (FitzSimons, Mlcek, Hull, & Wright, 2005). In all these contexts the stakes are high. If numeracy education and assessment can be made more authentic and meaningful in such safety-critical contexts, it should be possible to do the same in less pressurized contexts. Our work also offers a powerful new conceptualization of competence in numeracy for nursing which we hope will gain traction in other vocational areas where conceptualization, calculation and technical measurement need to come together (as shown in Figs. 2, 3 and 5, above).

Our research suggests that students should be exposed to a comprehensive range of vocationally appropriate and authentic tasks, problems and functional objects (artefacts) and associated symbology, in a safe environment in which the mathematical demands are present but no more explicit than they are in vocational practice. Dynamic virtual online simulation using combined iconic and symbolic representation offers a meaningful way of exposing and sensitizing students to the vocational mathematics-containing challenges they will meet in professional practice, raising their awareness of these challenges and giving them opportunities to *see* the problem, explore methods and solutions and practise at their own speed, away from the pressures of the workplace. Meanwhile, the increasing sophistication of online multi-user virtual environments (MUVEs) is blurring the line between the learning environment and the work setting, allowing for simulation of the inherent variability of workplace tasks. Such approaches can be effective. For example, Farra, Miller, Timm, and Schafer (2012) found that virtual reality simulation reinforced learning and improved learning retention of nursing students undergoing disaster training. While authentic simulation is particularly important in safety-critical contexts such as nursing, we believe it is important for all vocational areas.

Our findings strongly support the idea that numeracy skills (in the sense of numeracy used in this article) should be taught and learned in context, and that knowledge must be transformed into new context-specific knowledge, integrating experience-based judgment with the social and cultural norms of the workplace (FitzSimons & Coben, 2009). This is supported by Bakker and Akkerman's (2013) research, using a boundary-crossing approach that successfully supported students to integrate school-taught and work-related knowledge. More broadly, we believe our work contributes to a more holistic, ethical and democratic approach by recognizing the learner as the agent of his or her own learning, while reducing the theory-practice and knowledge-performance gaps perpetuated by the traditional organization of nursing and some other vocational education systems.

Following Wake and Williams (2001), our research supports an emphasis on the following:

- Using relatively *low-level* mathematics in quite complex situations and contexts, echoing Steen's (2004) often-quoted statement that "Mathematics in the workplace makes sophisticated use of elementary mathematics rather than, as in the classroom, elementary use of sophisticated mathematics" (p. 55)
- Encouraging experiences of a diversity of conventions and methods
- Having students experience activities where the mathematics is embodied in context and to use artefacts with which they have become familiar
- Preparing students to transform their existing mathematical knowledge to make sense of activities in unfamiliar workplace situations
- Having students design spreadsheet programmes for modelling and for the recording, processing and analysis of data and
- Making students aware that there are many and varied ways to solve any problem

In addition, Hoyles, Wolf, Molyneux-Hodgson, and Kent (2002) recommend (a) developing an ability to perform paper and pencil calculations and mental calculations as well as calculating correctly with a calculator; (b) calculating and estimating (quickly and mentally), including understanding percentages, multi-step problem-solving, use of extrapolation; (c) recognizing anomalous effects and erroneous answers when monitoring systems; (d) communicating mathematics to other users and interpreting the mathematics of other users; (e) developing an ability to cope with the unexpected; and (f) developing a sense of complex modelling, including understanding thresholds and constraints.

All vocational mathematics education must prepare students to become competent practitioners, able to exercise their judgment safely and effectively in meeting the mathematical demands of their work. The educator must therefore understand these vocational and mathematical demands—a challenge addressed by Casey et al. (2006) in their report entitled *You Wouldn't Expect a Maths Teacher to Teach Plastering*…. One way forward, which we recommend, is for vocational and numeracy experts to collaborate across disciplines, not necessarily in each teaching situation, but certainly in research and the design of vocational mathematics education programmes.

7 The importance of interdisciplinary collaboration

Disciplinary and vocational specialization is essential in the complex modern world, but it comes at a cost. Separate literatures encourage a clear focus on a particular discipline or vocational area at the expense of a broader interdisciplinary vision. For example, the vocational education literature in general does not focus strongly on mathematical issues and concerns. The literature on competence issues in safety-critical industries does not, in the main, focus on vocational mathematics; however vital vocational mathematics educators might believe their concerns to be for safety in those industries. Examples include Slaven's (1995) review of competence frameworks in the UK oil and gas industry and a recent report for the UK Health and Safety Executive, which mentions mathematics only in connection with entry requirements noted by industries contacted for the research (Wright, Turner, & Horbury, 2003). Similarly, with some honourable exceptions, the mathematics education literature is not centrally concerned with the mathematical demands of work: vocational mathematics education arguably still occupies a peripheral position in the literature on mathematics education (FitzSimons, 2002).

We believe that interdisciplinary collaboration to support authentic vocational mathematics education is important, especially in safety-critical contexts. Interdisciplinary work requires the development of boundary-crossing skills and integrated knowledge building (Spelt, Biemans, Tobi, Luning, & Mulder, 2009), and the boundary-crossing literature offers a lens through which to view such collaborations. Blackwell, Wilson, Street, Boulton, and Knell (2009) highlight the direct benefits of interdisciplinary collaborations as: "the creation of new ecosystems or intellectual ecologies within which other kinds of innovation can occur, or new questions be asked" (p. 4).

As noted above, the Reference Group research team is interdisciplinary, comprising registered nurses, nurse educators, an adult numeracy educator and a psychometrician, all of whom are expert in various qualitative and/or quantitative research methodologies. Such interdisciplinary research collaborations are unusual in vocational mathematics education, but in our experience, there is much to be gained in terms of mutual learning about the mathematical demands of the vocational context and ways of supporting practitioners to meet those demands. Experts in the different areas bring different insights and different ways of thinking and speaking about their work. Sharing these insights and translating between these discourses, for example, having to explain phenomena that may be taken for granted within one's own area to a colleague from a different area, becomes a joint responsibility, with the aim of understanding issues of mutual concern. Given the well-attested invisibility of mathematics in vocational contexts (Bakker, Kent, Noss, Hoyles, & Bhinder 2006), this is particularly valuable in vocational mathematics education.

8 Conclusion

The teaching, learning, assessment and safe-practice of vocational mathematics require the facilitation of uniform understanding and application of agreed benchmarks and taxonomies. This is particularly important in highly regulated practice-based and safety-critical professions like nursing and requires the profession's regulator, education establishments, clinical mentors and assessors and students to *learn to see* and to apply the form and content of agreed benchmarks and taxonomies. We have provided an exemplar competence model and authentic learning and assessment environment that act as a framework for supporting shared understanding, learning, assessment and clinical application of essential vocational mathematical knowledge and skills. Authentic competence models and environments of this type support the bridging of the theory-practice and knowledge-performance gaps, and we propose that our work acts as an exemplar for developing analogous models and environments within other domains of vocational mathematics. We plan to continue our work and hope others will also take up this challenge.

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