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Harnessing the power of virtual reality technology to enhance public health genomics skills in Africa

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Africa must sustainably bridge the public health genomics skills gap to build a workforce that responds with speed, quality, and scale. Virtual reality offers a novel and cost-effective solution to address this gap, but its implementation must follow best practices.

Snapshot of Africa's current workforce development efforts

Prior to the COVID-19 pandemic, many institutions, particularly national public health institutions (NPHIs) and national reference laboratories (NRLs), accounting for 87.3% (48/55) in Africa, had extremely limited genomics and bioinformatics literacy, expertise, and opportunities[1–3]. By 2021, only 62 (30.1%) of the 206 operational next-generation sequencing (NGS) devices on the continent were located at NPHIs and NRLs[2]. Since then, initiatives such as the East African Community Secretariat (in partnership with the Bernhard–Nocht Institute of Tropical Medicine)[4], Africa CDC's Africa Pathogen Genomics Initiative (Africa PGI), SeqAfrica[5], and designated centers of excellence have played integral roles in building, standardizing, accelerating, equitably advancing, and sustaining public health genomics in Africa[6,7]. These efforts have increased local pathogen genome sequencing, shortened turnaround times, and enhanced routine surveillance[5,7]. Currently, most NPHIs and NRLs (83.6%, 46/55) have functional NGS infrastructure, and nearly all (96.4%, 53/55) have foundational-to-advanced data analysis capabilities[8].

Despite these advances, efforts must be expanded and sustained to keep pace with rapidly evolving NGS technologies and public health needs[9], while addressing the long tail of existing workforce development gaps and challenges, including infrastructure constraints, poor funding for sustainability[4,8,10,11], limited inclusion of underrepresented groups[12], and insufficient training cascade models to minimize human errors. End-to-end, in-person pathogen genomics training in Africa is costly, averaging approximately US$ 800 per trainee per day (range: US$ 500–1200) during 2021–2026, depending on training logistics and resources. As public health genomics expands beyond pathogen surveillance to population genetic screening, pharmacogenomics, and precision medicine, skills gaps and mismatches are likely to emerge. Virtual reality (VR), therefore, presents an innovative, scalable, and cost-effective solution to bridge the divide between theoretical knowledge and practical skills[13]. Here, we highlight VR's potential for skilling, reskilling, and upskilling the public health genomics workforce in Africa and beyond, aligned with the United Nations 2030 Agenda and African Union Agenda 2063.

Time for VR to converge with public health genomics

Conventional workforce development methods in public health genomics, including e-learning and in-person workshops, have been beneficial but remain insufficient to rapidly build local expertise while mitigating costs, brain drain, and limited access to on-demand and advanced training. There is a call for transformative and sustainable strategies to address these gaps. Extended reality (XR) experiences such as VR, augmented reality (AR), and mixed reality, as defined in Fig. 1, offer promising solutions. VR and AR are effective tools for administering visual and auditory learning content, respectively. However, their effectiveness depends on context and the extent of user interaction and engagement[14], which should not be assumed to be universally beneficial across all applications. In this *Perspective*, we emphasize the use of VR for education and training.

VR has been applied in STEM education[14–16], medicine[17–23], and industrial enterprise[24], demonstrating improvements in surgical accuracy[18], cognitive rehabilitation[19], university-level science teaching[15], mines rescue[25], and firefighting skills[26], and industrial maintenance across the product lifecycle[27]. VR can reduce training

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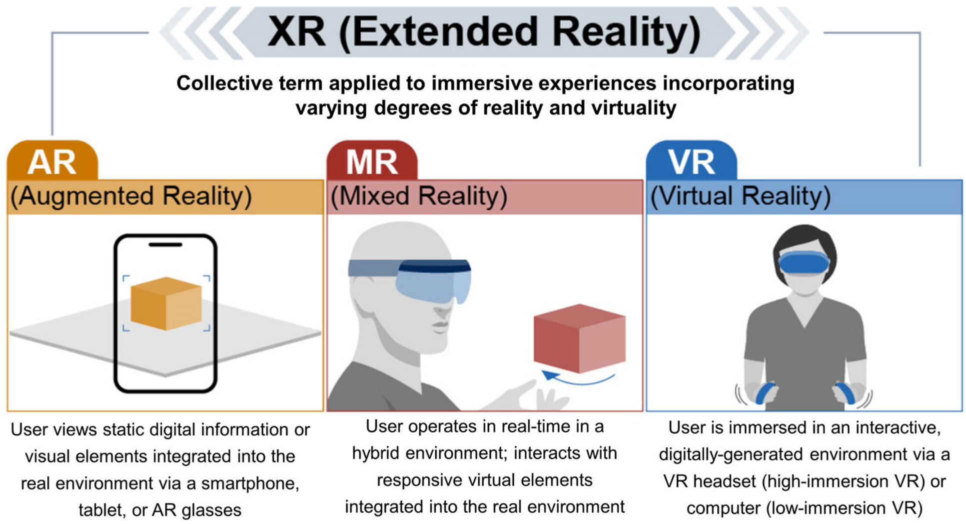

Fig. 1 | The continuum of extended reality. Augmented, mixed, and virtual realities largely depend on the level of interactivity (digital versus real-world experience) and perception. The image is modified and used with written permission from the U.S. Government Accountability Office (GAO)[47].

BOX 1

Pedagogical frameworks and examples for VR-based learning in public health genomics

- **Constructivism**. Is the most utilized and allows learners to actively construct knowledge[57] by engaging in a range of activities such as interpreting variant calls, constructing phylogenetic trees, and annotating genomes to support outbreak investigation and public health decision-making. Constructivist VR encourages autonomous exploration within the VE.
- **Experiential learning**. Is deemed the most appropriate for VR applications, as it promotes autonomous learner engagement within the VE, thereby facilitating self-directed exploration and decision-making[57]. Trainees engage with and reflect upon their experiences through tasks such as laboratory sample processing, mock NGS runs (including metagenomics), and pathogen detection simulations in a risk-free VR environment. This approach promotes self-directed exploration, practical skill acquisition, and reflective learning.
- **Learning by doing**. Emphasizes active and supports hands-on engagement to strengthen procedural understanding. Here, learners acquire knowledge and skills through direct experience rather than passive observation. It allows trainees to perform realistic laboratory procedures such as pipetting, nucleic acid extraction, library preparation, or sequencing within a VE that provides immediate feedback.
- **Learning through problem-solving**. Centers on solving real-world, open-ended problems to drive learning. Within a VE, trainees encounter simulated challenges such as diagnostic troubleshooting, identifying contamination sources, or interpreting ambiguous variant data, and must apply analytical reasoning to find solutions. This approach develops practical competence, critical thinking, and integrative reasoning.
- **Gamification**. Challenge-based, gamified VR exercises incorporate time constraints, scoring, leaderboards, and scenario branching to emulate operational pressure and facilitate engagement. For example:

  - ***Time constraints:*** Require trainees to complete tasks such as PCR setup, sequencing library preparation, or data analysis within a limited period to simulate the urgency of real laboratory workflows.
  - ***Scoring system:*** Includes a reward mechanism and penalties for mistakes, such as providing rewards for correctly performing the execution of pipette steps (e.g., aspirating and dispensing the exact volume of liquid, following proper technique by keeping the pipette vertical and avoiding bubbles, changing tips to avoid contamination), or point deductions for achieving inaccurate genome assembly or incorrect pathogen variant identification. This provides immediate feedback and buttresses proper technique and accuracy.
  - ***Leaderboard:*** Ranks trainees individually or in teams based on measurable performance metrics such as completed tasks, accuracy, and speed during simulated variant detection.
  - ***Scenario branching:*** Adapts the workflow based on user actions, e.g., if a trainee selects the wrong sequencing chemistry, the workflow fails and requires troubleshooting before advancing, or if a sample is mishandled and safety procedures are not followed, the VR simulation can cause the trainee to become "infected", prompting corrective actions before proceeding. Scenario branching can further integrate both *adaptive complexity*, in which task difficulty is dynamically adjusted in real time based on learner performance, as well as *progressive task difficulty*, where tasks increase in complexity according to a predefined sequence.

time[18], improve knowledge retention and competency[14,18,28–30], enhance understanding of abstract concepts and novel ideas[15], and support mental model development[28], although outcomes may vary[31]. Thus, adopting standardized protocols, VR devices, and evaluation metrics can help reduce variability and strengthen the evidence base.

Various educational approaches (learning theories), such as constructivism, experientialism, gamification, learning by doing, and learning through problem-solving, have been used in VR (Box 1). Combining VR with the 6E model (Engage, Explore, Explain, Engineer, Enrich, and Evaluate)[32], and STEM education to cultivate hands-on activities can enhance learning by doing[28]. Here, virtual environments

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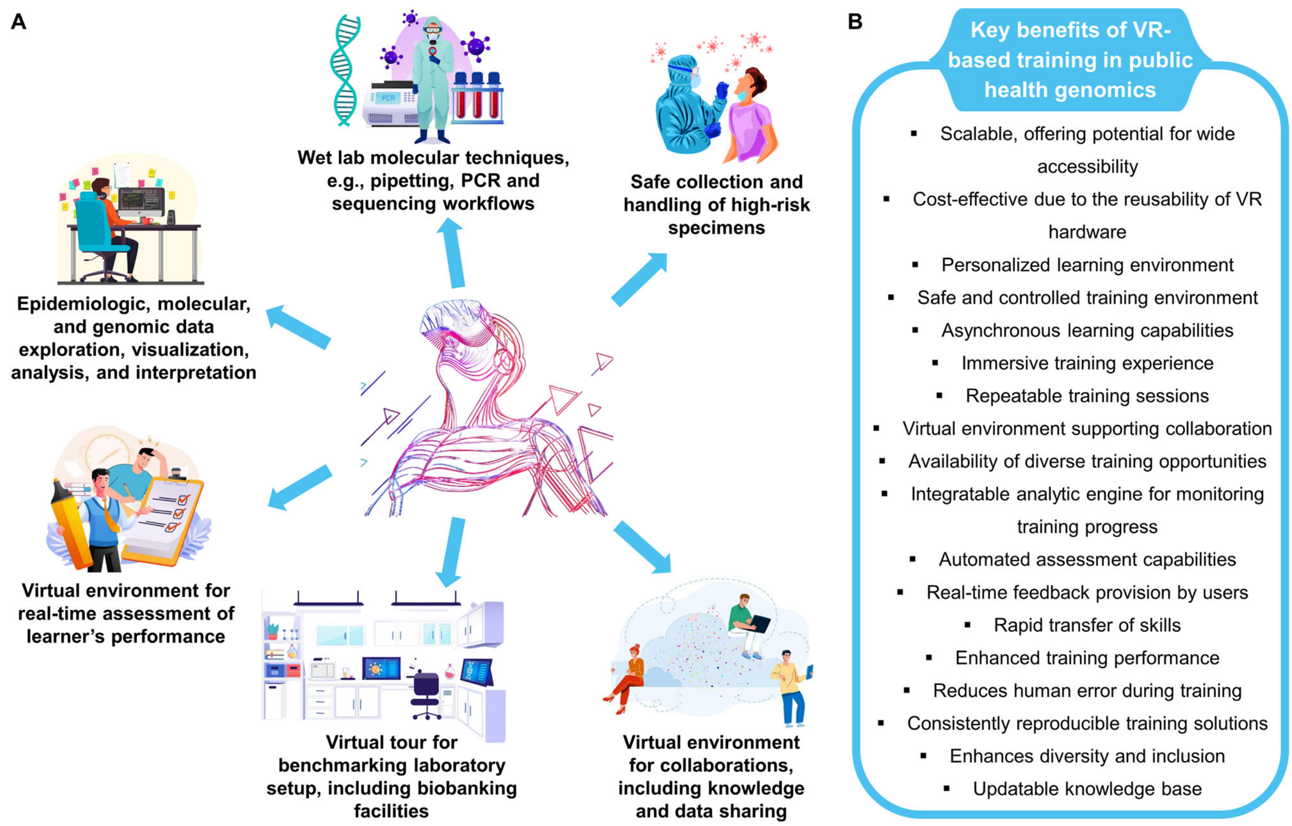

Fig. 2 | Application of virtual reality (VR) technology in the public health genomics domain. A VR can support practice-based learning and training in safe sample collection and handling, wet lab molecular techniques (including pipetting, PCR, and sequencing workflows), bioinformatics data exploration and analysis, evaluation of trainees' performance, virtual laboratory tour guides to remote collaboration for knowledge and data sharing in shared virtual environments through avatars. **B** Potential benefits of VR technology in public health genomics. Graphical elements in (**A**) adapted from stock images designed by Freepik (www.freepik.com) and from images licensed from both Shutterstock and iStock (Getty Images).

(VEs) can be designed to operationalize each stage of the 6E. For example, learners can "Engage" with immersive outbreak scenarios, "Explore" and "Explain" virtual genomic datasets and laboratory workflows, "Engineer" and "Enrich" intervention strategies or sequencing pipelines, and "Evaluate" their decisions using VR-based feedback and practical results, thereby strengthening both conceptual understanding and hands-on skills.

Africa PGI's NGS Academy has developed a standardized, competency-based, context-specific public health genomics curriculum that can be leveraged in VR training. VR capabilities can be aligned with specific public health laboratory tasks, offering immersive, standardized, and risk-free training VEs. These range from interactive virtual patients or field scenarios for sample collection to shared VEs for knowledge sharing (Fig. 2A). Modules can support technical documentation review[33] and simulate core biosafety procedures such as operating biosafety cabinets, donning and doffing personal protective equipment in outbreak settings[29,34], and field-based tour (including hazard visualization in wastewater industry[35]). VR is particularly useful in risky, non-replicable, or resource-limited settings where reagents, equipment (e.g., thermocyclers), and sample numbers are restricted[30,36]. Step-by-step guides in VEs can train users in sample processing (e.g., preparing serum or plasma from blood) and in standardized biobanking workflows. These applications align with the DICE (Dangerous, Impossible, Counterproductive, or Expensive) framework[37], highlighting VR's effectiveness for high-risk or constrained public health genomics tasks.

In pathogen genomic surveillance, VR-based training virtually eliminates the risk of infection and disease spillover. In certain scenarios, VR-based training may require guided-education or supervision to prevent hazardous incidents in the real environment and distortion of the learning process[18]. VR can facilitate virtual drills[21] and other complex and costly training events that occur less often[20,24]. Virtual wet laboratories can guide learners through molecular techniques, including pipetting, reagent preparation, and use (e.g., buffers, primers, enzymes)[38], nucleic acid extraction, PCR, and sequencing setup and workflows[36,38,39] (including onboarding new workflows and operating new instruments[30,38]), gel electrophoresis, and specialized applications such as CRISPR technology[40]. VR supports advanced visualization and immersive analytics for multi-omics and molecular data exploration and interpretation[41], and enables 3D user interfaces for graphical genome interaction and analysis[42]. It can further strengthen bioinformatics and computational competencies, including operator training and the setup and maintenance of high-performance computing resources, as demonstrated in manufacturing engineering[43]. VR also enables inexpensive virtual laboratory tours[16], collaborative VEs for knowledge and data sharing, with highly expressive avatar control systems[44], and multilingual learning experiences[45]. While VR-based training may outperform traditional classroom methods, it complements rather than replaces them[15,20,24,29].

VR technology has great potential to decentralize and revolutionize public health genomics, but remains largely unexplored. Currently, there are few XR initiatives on the continent, though ongoing efforts aim to increase literacy and practical experience through conferences, bootcamps, and exchange programs. Uganda's African Center of Excellence in Bioinformatics and Data Intensive Sciences (ACE) is using VR to support in-country learning, training, and diagnostics, with a focus on healthcare, including basic life support, surgery, and COVID-19 infection prevention and control[29]. The Centre for Data Science and

VR at Nigeria's Institute of Genomics and Global Health is developing XR and artificial intelligence (AI) tools to teach laboratory workflows and genomic sequencing. Meanwhile, Senegal's Centre for Africa's Resilience to Epidemics at Institut Pasteur de Dakar has launched a training facility for VR and AR. Such initiatives have established foundational infrastructure, including trained VR instructors, technical expertise, and VR-ready facilities (e.g., low-cost headsets and smartphones[46]) that can be leveraged for continent-wide public health genomics training.

Benefits of VR in public health genomics capacity building

The application of VR technology in public health genomics workforce development provides multiple benefits (Fig. 2B). As a cost-effective, scalable, and reusable tool, VR can rapidly meet demand for specialized skills while overcoming financial, time, and logistical constraints for individuals unable to travel for in-person training[21,24]. It promotes equity, diversity, and inclusion[36] by offering barrier-free, customizable learning environments[18], particularly in under-resourced settings. VR-based training minimizes human error, ensures consistency and replicability, and enables safe simulation of DICE-aligned tasks[18,20,26,29]. VEs can allow users to "shrink" into biological and genetic landscapes to explore biological processes and the genetics of health and disease[40], visualize pathogen genome organization, track PCR steps, and observe sequencing processes. VR supports experiential and repeatable learning as well as captivating encounters that boost their intellectual capacity[26] and skill retention[14]. It enables asynchronous, self-paced training[24,29]. Integrated VR analytics can monitor task execution and time on task during training[20], enable automated performance assessment[22], and support real-time monitoring of learners' emotional and attentive states using biometric indices[24]. VR knowledge base remains accessible and updatable with evolving practices and technologies. VR also supports digital workspaces for remote collaboration[33,44], including secure data sharing[47].

VR integration: barriers, facilitators, and mitigation measures

To date, no studies have systematically examined barriers and facilitators to VR uptake and routine use in public health genomics. Evidence from other fields indicates cross-cutting, context-specific factors across individual, structural, organizational, technical, and health-related dimensions[47–50]. Individual barriers include inadequate training, low digital literacy, usability concerns, preference for traditional approaches[20], concerns regarding excessive mechanization of work[51], and negative perceptions or doubts about technical competence[48,50,51]. These barriers can be mitigated through mentoring, "train-the-trainer"[50] and champion models[52,53], and user-centered design supporting tailored learning[23] and user interest and satisfaction[49]. Structural challenges include unstable internet connectivity[46], which is common in Africa[54], and high upfront hardware cost[18,21,23,46,48,49], which may become cost-effective over time via equipment reusability, technological advancements[21,22,24,29], local manufacturing, and public-private partnerships (PPPs). Currently, the main cost of VR lies in the personnel costs for content creation[21]. Organizational constraints include resistance to innovation, technological unfamiliarity, insufficient leadership support[22,48], weak institutional policies[48], and data security and privacy risk, indicating the need for leadership advocacy, institutional buy-in, awareness campaigns[50], and governance frameworks[37,47]. Technical and health-related challenges, including unmet user needs[49], insufficient instructor skills[29], and technical support[50], content creation difficulties, poor-quality visuals[48], and hanging graphics[51], absence of evaluation metrics, cybersickness[26,47,49,55], rare visual hallucinations[56], and minor, transient discomforts[57,58], are addressable through standardized frameworks, optimized VR design[55,59,60] (including AI integration), and content exposure strategies[26,61].

VR in public health genomics: from concept to implementation

The design and implementation of VR training in pathogen genomics require a structured, best-practice-driven approach to ensure effectiveness and demonstrable advantages over traditional methods. AR/VR has been utilized for skills development in molecular biology laboratories to engage with DICE-aligned workflows otherwise constrained by biosafety and resource limitations[36]. VR implementation in pathogen genomics follows a systematic process: assessing competency gaps, defining learning objectives, selecting appropriate head-mounted displays, developing accurate 3D procedural laboratory models, creating interactive content, integrating feedback and assessment tools, rigorous testing, deployment, and data-driven monitoring and evaluation (Supplementary Table 1). Key considerations include simulation facilities, technical personnel, quality assurance and risk management, biosafety, ethical safeguards, mitigating both biomechanical data privacy risks[62–64] and digital issues (e.g., digital clutter, AI-generated slop, and adversarial cyberattacks), usage monitoring to prevent overexposure or addictive behavior[23,57,65], and inclusion of champions to promote VR adoption[52,53].

Next steps for VR technology in public health genomics

The global VR market is poised for substantial growth due to technological advancements and an increasing demand for a competent, adaptable, and interoperable workforce[47], particularly in Africa, where traditional training is inadequate, costly, and occasionally inequitable, presenting an opportunity Africa should capitalize on. Despite the growing promise, interest, and adoption of VR-based training[25,29], next steps must prioritize robust data security to mitigate cyberattacks[22,47] and ethical frameworks to ensure VR complements human engagement[51]. Optimization should follow a data-driven scientific approach, including validation of hardware and simulated tasks, and caution in extrapolating findings from other fields with differing constraints[21,50]. Sustainable deployment further depends on stakeholder engagement[21], funding, continent-wide mapping exercises, cost-benefit analysis[21,22], a theoretical framework to guide implementation[50], common standards for content development, a creation pipeline of VR training (that includes task analysis, training scenario sketching, and implementation steps)[24], modular-based exercises for training and examination purposes[21], skilled local capacity, ergonomic hardware, context-appropriate solutions (for low-bandwidth and unreliable power supply settings[54]), consideration of learners' spatial acuity[66], integration with AI[67] and Internet of Things (IoT)[68] (for scalable, intelligent, adaptive, and personalized or collaborative training), quality assurance, pilot-to-scale programs, and trusted PPPs. Detailed operational and technical considerations are provided in Supplementary Table 1.

Final thoughts

Prohibitive costs and resource requirements of non-VR training position VR as a reliable and cost-effective alternative[21,24], provided it is safeguarded against unethical use and content and security risks. VR presents a timely opportunity to address the skills gap and mismatch in public health genomics amid limited resources, rapid digital transformation, and talent drain. Africa CDC is strategically positioned to catalyze locally relevant VR trainings through coordinated pilot programs in established, genomics-focussed institutions (with ongoing VR initiatives), open-source learning platforms, content-sharing hubs, and enabling infrastructure, including the ongoing regional roll-out of Starlink. Successful adoption and diffusion of VR must align with technological infrastructure, policy decisions, economic resources, sociocultural factors, and the DICE framework[37].

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Author contributions

H.O. conceptualized the idea in the manuscript. H.O. wrote the first draft of the manuscript. H.O. performed visualization. H.O., C.K.T., A.A., A.K., M.M.D., and S.K.T. contributed to the reviewing and final approval of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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