Including Cultural Context Improves Communication Outcomes for Quaternary Geoheritage: Evidence from Southeast Arabia

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Abstract. Effective science communication plays a crucial role in enhancing public understanding of Quaternary science. One potential strategy for advancing public engagement involves highlighting the interconnectedness of Quaternary sites, archaeology, and human culture. Despite the recent increased focus on science communication within the geosciences, the significance and effectiveness of emphasising such geocultural connections in communicating about Quaternary geoheritage sites have rarely been explored in experimental settings.

This study investigates the efficacy of educational videos in communicating the significance of Quaternary geoheritage sites in southeast Arabia. Specifically, it examines the impact of including geocultural context information. An online experiment was conducted to evaluate the effects of videos produced with input from academics, museum professionals, and heritage administrators from the region. The study compares the impact of two different 9-minute videos—one emphasising the geocultural context, and the other focusing solely on Quaternary science—on participants' knowledge, interest, and perception of Quaternary geoheritage sites.

Both videos were found to be effective overall in enhancing participants' self-reported knowledge of Quaternary geoheritage sites and increasing their interest. However, the inclusion of geocultural information resulted in a stronger sense of the need to protect Quaternary geoheritage sites and promoted sustained interest in the geocultural relationship, especially among non-specialists. Moreover, although the geocultural video may have been less effective as an immediate teaching tool compared to the Quaternary science-focused video, the learning outcomes were comparable between the videos in the medium-term. Although the participant number is small and demographically limited to highly educated, relatively young adults with pro-nature attitudes, this study advances our understanding of the role of geocultural connections in communicating the importance of Quaternary science and raising awareness of Quaternary geoheritage.

By demonstrating the benefits of incorporating information on cultural relevance into communication strategies, the study illustrates how Quaternary scientists and geoheritage practitioners can enhance audience engagement, support understanding, and inspire lasting changes in attitudes. These positive findings underscore the necessity for future research to explore the applicability of this concept in various social, cultural, and/or geographical settings.

1 Introduction

Quaternary science holds significant relevance for society, with implications for climate change, sea level oscillations, coastal erosion, geohazards, historical biodiversity, and human evolution (Elias, 2007). Furthermore, Quaternary processes have shaped numerous distinctive landscapes, some of which have been protected internationally. According to Boylan (2008), 17% of all World Heritage Sites characterised by geological features predominantly represent Quaternary features, including karstic landscapes (e.g. Plitvice, Croatia), deserts (Lut Desert, Iran), or volcanoes (Hawaii Volcanoes National Park, USA), despite this period only representing 0.057% of Earth's history. However, many geological heritage sites, or geoheritage sites, have been protected (Chylińska, 2019) and visited (Štrba, 2019) for their aesthetic appeal rather than their scientific significance or appreciation, with Quaternary sites being no exception.

In both the World Heritage List (Boylan, 2008) and the Global Geopark Network (Brilha, 2018), Quaternary sites predominantly feature glacial, karstic, or volcanic formations, aligning with the classic definition of natural beauty (Churchward et al., 2013; Mitchell, 2013). Consequently, the communication and promotion of geoheritage sites, particularly concerning their scientific and societal importance, have emerged as crucial agendas (Gordon et al., 2018; Stewart & Nield, 2013).

Recognising the cultural significance of Quaternary sites presents a potential avenue to enhance their appreciation among the general public. This concept, known as geocultural heritage (Kubalíková et al., 2020; Reynard & Giusti, 2018; Sayama et al., 2022), offers alternative pathways for non-experts to connect with these sites. Various studies have explored how specific sites embody interdisciplinary heritage values (Coratza et al., 2016; Gravis et al., 2017; Kazancı & Lopes, 2022; Mariani & Melis, 2022). However, the practical efficacy of this concept in interpreting and promoting Quaternary geoheritage sites has received limited attention, particularly in terms of input from the relevant publics. By using documentary-style videos to introduce Quaternary geoheritage sites to the public in southeast Arabia (i.e. the UAE and Oman), this study aims to provide data to help advance effective science communication of Quaternary geoheritage and evaluate the utility of the geocultural concept in this process.

1.1 Geoheritage and cultural heritage

Geoheritage sites, by nature demonstrate strong geoscientific values, but its importance expands to cultural dimensions as well. The relationship between geoheritage and culture are becoming increasingly studied, understood, and recognised. Studies have emphasised that this complex relationship is expressed through multiple, interconnected pathways (Pijet-Migoń & Migoń, 2022; Reynard & Giusti, 2018). As components of landscapes, geoheritage sites often hold symbolic and spiritual meaning, reflected in religious traditions that attribute sacred status to features such as rocks and caves (Kiernan, 2015). Geological processes and events are also embedded in cultural memory through oral traditions and place names, which record volcanic eruptions, earthquakes, and tsunamis and, in some cases, contribute to long-term risk awareness and disaster preparedness (Ludwin et al., 2007; King & Goff, 2010; Fepuleai et al., 2017; Sousa et al., 2010; Planas-Batlle et al., 2023; Fontanella Pisa, 2024; Isoda et al., 2019). In addition, geoheritage sites can provide essential contextual information for archaeological research by reconstructing palaeogeographic settings and documenting past human–environment interactions (Panizza & Piacente, 2009; Melelli et al., 2016; Coratza & Hobléa, 2018; Fairchild & McMillan, 2007). Geological materials and landforms have also been widely used in the construction of settlements, infrastructure, and cities, forming the basis of urban geoheritage and offering opportunities to connect geosciences with everyday human experience (Boukhchim et al., 2018; Coratza et al., 2016; Kubalíková et al., 2020; Pica et al., 2018). Together, these cultural dimensions highlight the need for holistic approaches to geoheritage conservation and communication that integrate scientific, cultural, and societal perspectives. Moreover, this geocultural framing can be utilised for more specific contexts such as Quaternary geoheritage.

1.2 Quaternary Geoheritage and its cultural dimension

Quaternary geoheritage sites encompass geological/geomorphological sites whose primary heritage values originate in the Quaternary period (Sayama, 2024). This concept represents a broader interpretation of geomorphosites (sensu Reynard et al., 2009), which defines aesthetic characteristics as a key (but not sole) attribute. In general, Quaternary geoheritage sites demonstrate three main characteristics (Reynard, 2009; Sayama, 2024). Firstly, many Quaternary geoheritage sites are dynamic, as they are strongly influenced by ongoing earth surface processes. These sites offer opportunities for observing current earth dynamics and are relatively susceptible to changes through weathering and other natural processes. Consequently, Quaternary geoheritage sites may undergo transformations in their form, which may not always align with their aesthetic value. Secondly, these sites can exist at various scales, ranging from those covering entire landscapes, such as alluvial plains, to smaller individual features. Finally, many Quaternary geoheritage sites exhibit strong connections with human culture, encompassing archaeological, historical, architectural, and other dimensions. These sites were formed, are forming, or will be formed, concurrently with human history. Given this synchronicity, Quaternary geoheritage sites can provide geoarchaeological records of the human-environment interactions over time and document the impact of humans on this nature-culture relationship. Moreover, Quaternary geoheritage sites have inspired creative ingenuity in art and cultural traditions, as exemplified by the religious and artistic significance of Mount Fuji, Japan (Chakraborty & Jones, 2018; Oguchi & Oguchi, 2010), or the importance of Holocene meteorite impact craters in Australia for Aboriginal dreamtime stories, some with an oral history dating back approximately 4500 years (Hamacher & Goldsmith, 2013).

Given these distinctions, many geoheritage studies (Erhartič, 2010; Moradi et al., 2021; Pereira & Pereira, 2010; Pereira et al., 2007) have treated Quaternary sites (or geomorphosites) separately from the rest of geoheritage sites. This differentiation is particularly evident in site evaluations, which place added emphasis on encompassing cultural and aesthetic dimensions of Quaternary sites. However, the necessity of such a differentiation is still debated with contradicting outcomes depending on the study. On one hand, Santos et al. (2020) found notable differences in evaluating sites in Brazil and Switzerland between methods developed for general geoheritage sites and specialised methods for geomorphosites. However, in a similar analysis, Mucivuna et al. (2022) found no significant differences between general and specialised methods, concluding that existing general methods should be used in the future to maintain consistency amongst various studies. In arid environments, Sayama (2024) identified distinctive features when developing a method for the scientific evaluation of Quaternary geoheritage sites, including the consideration of connections with archaeology/anthropology, with greater importance placed on scientific knowledge. Nevertheless, the geocultural dimension of Quaternary sites has not been studied in detail from the perspective of science communication. Therefore, further investigation is required to understand the importance and utility of different strategies, including the incorporation of the cultural dimension of Quaternary geoheritage sites.

1.3 Quaternary Geoheritage Sites in Southeast Arabia

Southeast Arabia is a region with a diverse array of Quaternary landscapes, including alluvial fans (Blechschmidt et al., 2009; Parton, Farrant, et al., 2015a), caves (Fleitmann et al., 2003; Immenhauser et al., 2007), palaeolakes (Rosenberg et al., 2012), sabkhas (Heathcote & King, 1998; Matter et al., 2015), and sand dunes (Atkinson et al., 2013; Goudie et al., 2000; Leighton et al., 2014; Radies et al., 2005). Research conducted at these sites has significantly advanced our understanding of environmental variability during the Quaternary, and its impact on human demographics. Throughout the Quaternary, the landscape of southeast Arabia experienced alternating wetter and drier conditions, corresponding to 100k-year eccentricity (Parker et al., 2004; Rose et al., 2019) and 23k-year precessional cycles (Parton, Farrant, et al., 2015b; Preston et al., 2015). By integrating archaeological and palaeoclimatic data, researchers such as Parker (2009) and Parton et al. (2015) have highlighted the close correspondence between early human settlement and environmental variability in this region. This connection underscores the importance of Quaternary palaeoenvironmental sites not only as climatic archives but also as geocultural sites with relevance for regional archaeology and culture. These geocultural connection have been acknowledged by various Quaternary scientists (Atkinson et al., 2013; Farrant et al., 2015; Nicholson et al., 2020; Preston et al., 2015; Rosenberg et al., 2012; Zerboni et al., 2020) who cite archaeological relevance as a primary motivation for conducting their palaeoenvironmental research.

However, only a limited number of studies have considered these Quaternary sites as heritage sites requiring and/or deserving conservation, despite various reports of their loss. A recent inventory of Quaternary palaeoenvironmental sites in this region identified the destruction of 31 out of 234 sites (13%) along with endangerment of 34 sites (15%) (Sayama et al., 2022), primarily due to urban development and quarrying. On the scale of individual sites, Lokier (2013) and Kirkham and Evans (2019) have emphasised the endangerment of the Abu Dhabi Sabkha, UAE, illustrating how recent developments in petroleum and civil engineering activities have damaged over 60% of this landscape with unique heritage values. The loss of Quaternary sites has also been documented in palaeoenvironmental studies, such as Atkinson et al. (2011), where sites were destroyed by industrial development (Preston et al., 2015).

1.4 Science Communication on Geoheritage and Geosciences

The lack of appreciation of geosciences and geoheritage has been extensively documented from various perspectives. Although recent global initiatives such as the Global Geoparks Network have aimed to promote and protect geoheritage sites, visitors to geoparks often prioritise natural beauty (Štrba, 2019; Zgłobicki & Baran-Zgłobicka, 2013) or the curiosity of exploring new places (Allan et al., 2015; Chrobak et al., 2020; Farsani et al., 2019). On social media, the hashtag “geology” has been used approximately 80% less than “physics”, “biology”, or “chemistry” (Zawacki et al., 2022). Even when the media features geosciences, Stewart and Nield (2013) found that topics broadcasted on British television were largely limited to a few popular domains, including palaeontology, volcanology, and seismology, with a range of featured Quaternary topics mainly related to geohazards or archaeology. These findings highlight the clear need for improvement in the public recognition of geosciences, including Quaternary science.

Effective communication strategies have garnered attention and recognition as potential solutions to this apparent “detachment” (Stewart & Nield, 2013, p. 699) from geosciences. As described by Illingworth et al. (2018) and Rodrigues et al. (2023), geoscience communication is still at its infancy as an academic field with further need for formalisation and identification of its discipline-specific challenges. Nevertheless, key issues such as the difficulty of understanding deep time (Bowring, 2014; Trend, 2001; Warmold, 2017), unfamiliarity with technical jargon (Kortz et al., 2017; Ren et al., 2013), and the global lack of geosciences education in schools (Melendez et al., 2007; Reis et al., 2014; Subedi et al., 2020), have been identified as hurdles to wider appreciation and understanding of geoheritage sites and geosciences.

Over the last 10–15 years, various creative approaches have been developed to enhance geoscience communication, including information panels (Bruno & Wallace, 2019; Pasquaré Mariotto & Venturini, 2017), 3D models/virtual site visits (Dolphin et al., 2019; Hoblea et al., 2014), animations (Lansigu et al., 2014), poetry (Illingworth, 2023), mobile applications (Cayla, 2014), and dance (Matias et al., 2020). Regardless of the approach, many studies share the common theme of storytelling (Illingworth, 2023; Matias et al., 2020; Migoń & Pijet-Migoń, 2017; Stewart & Nield, 2013; Van Loon et al., 2020), praising its utility in delivering information in ways that connects with the audience cognitively and emotionally (Dahlstrom & Scheufele, 2018).

However, in analysing these initiatives, only a few studies have conducted qualitative or mixed-method assessments of the impacts of interventions. Matias et al. (2020) conducted such an analysis to evaluate the impact of a creative dance programme for elementary school education on coastal geomorphology and hydrology. In this study, more than 60% of the 112 participating students preferred learning science through movement, rather than in conventional settings. Another study by Mani et al. (2016) found a 12–17% improvement in participants’ knowledge on volcanic hazard after playing a video game on the topic. These impact assessments demonstrate the potential of geoscience communication but have mostly been limited to evaluating the short-term, immediate effects of the interventions, with no data beyond those collected immediately after the experience. Given the goal of geoscience communication to increase public discussion and attention to geosciences (Illingworth et al., 2018), longer-term assessments are required to capture a more comprehensive picture of the impact of interventions.

1.5 Science Communication Studies using Online Video

Videos have been used in scientific communication studies across various fields, including ecology (Ruzi et al., 2021), climate science (Ettinger et al., 2021), and medical sciences (Dudley et al., 2023). The preference for using videos stems from several advantages they offer. Firstly, delivering information in person or through videos and other visual media has been found to outperform written text in 15 studies (Dudley et al., 2023). Secondly, videos facilitate enhanced emotional engagement of the audience (Yadav et al., 2011) and easier comprehension through the combination of narration and images (Moreno & Mayer, 1999). For example, in discussing climate science, videos were found more effective than written text in communicating the consensus amongst scientists that current climate change issues are triggered by anthropogenic activities (Goldberg et al., 2019). Finally, as a method, videos offer the advantage of "making communication visible" (Goldman & McDermott, 2007, p. 112) by capturing and enabling the analysis of the effect of a specific content in a controlled manner, unlike personal communication, which can vary in its delivery.

Recognising the importance of videos in science communication, studies have provided guidelines for developing effective videos. Desired features included visual attractiveness, brevity, engaging content, and consideration of the audience needs and expectations (León & Bourk, 2018). Regarding the length of educational videos, multiple studies (Guo et al., 2014; Kaim et al., 2020; Manasrah et al., 2021) have found the optimum length of videos to be around 6–9 minutes. In Guo et al. (2014), eye-tracking of participants showed that viewers lost attention when videos exceeded 9 minutes, with engagement lasting less than 50% of the video's duration. To create an engaging video, Brame (2016) has demonstrated the need for enthusiasm from the narrator, the use of conversational language, and an emphasis on the relevance of the content.

Academically, videos can be used to analyse changes in opinions or knowledge after viewing (Dunn et al., 2020; Kaim et al., 2020), or to compare different communication methods, such as the relative effectiveness of various strategies in communicating a topic to the public. For example, Ettinger et al. (2021) used short videos to compare differences in viewers' reactions to videos with a pessimistic or an optimistic outlook on the trajectory of climate change. In geoscience communication, however, the utility of videos has seldom been studied quantitatively. One of the notable exception is Zawacki et al. (2022), who analysed the relative success of 48 geoscientific Tik Tok videos. This study found that while the most viewed videos were short clips related to news events, longer videos, which received fewer views, garnered the most user engagement. Given the demonstrated efficacy of videos in communicating science and technology, there are further opportunities to test their applicability for geoscientific topics.

1. Aims of the study

As outlined above, there is a need for further investigation into science communication regarding Quaternary science and Quaternary geoheritage. This study addresses this knowledge gap by analysing reactions to two 9-minute videos: one that describes Quaternary geoheritage sites of southeast Arabia with their geocultural context, and another that presents the same type of sites through a solely geoscientific lens, among primarily university-educated, pro-nature adult residents of Oman and the UAE primarily in their 20s and 30s. The study aims to evaluate whether these videos can improve knowledge, interest, and perceived importance of protecting Quaternary geoheritage sites in southeast Arabia, and to examine whether including geocultural connections enhances communication outcomes compared to a purely geoscientific approach.

2 Regional Setting

Southeast Arabia (Fig. 1) is situated within the arid subtropical climate belt, spanning approximately 16°4′ N and 26°4′ N, with the Rub'al Khali Desert to the west and the Hajar Mountains to the east. Presently, the climate of this region is hyper-arid, characterised by an annual rainfall of less than 100 mm in most areas, except for the area around the Hajar Mountains, where it can reach up to 400 mm (Kwarteng et al., 2009). Geologically, Quaternary deposits cover approximately 44% of the land surface (Fig. 1). The types of Quaternary landscapes in the region include aeolian (57%), alluvial (24%), fluvial (14%), sabkha (5%), and others (>0.1%). The Rub'al Khali and the Wahiba sands are the primary areas covered by aeolian sediments in this region. In this arid region, sparse vegetation and extensive exposures of dunes, alluvial fans, coastal terraces and cave deposits make Quaternary landforms and sediments highly visible in the landscape. This contrasts with many humid, vegetated environments, where Quaternary features are more often obscured and may be less immediately recognisable to non-specialists.

Socioeconomically, both the UAE and Oman have undergone major economic development over the past two decades, with GDP growth exceeding 300% driven largely by the expansion of the oil industry (Pirlea, 2023a, 2023b). This growth has been accompanied by high proportions of migrant residents (United Nations Population Division, 2024) and rising tertiary education levels (World Bank, 2023). However, opportunities for geosciences education remain limited in both countries, particularly at the school level (Al Ghfeli, 2016; Ambusaidi & Al-Balushi, 2015; Ministry of Education, 2023)

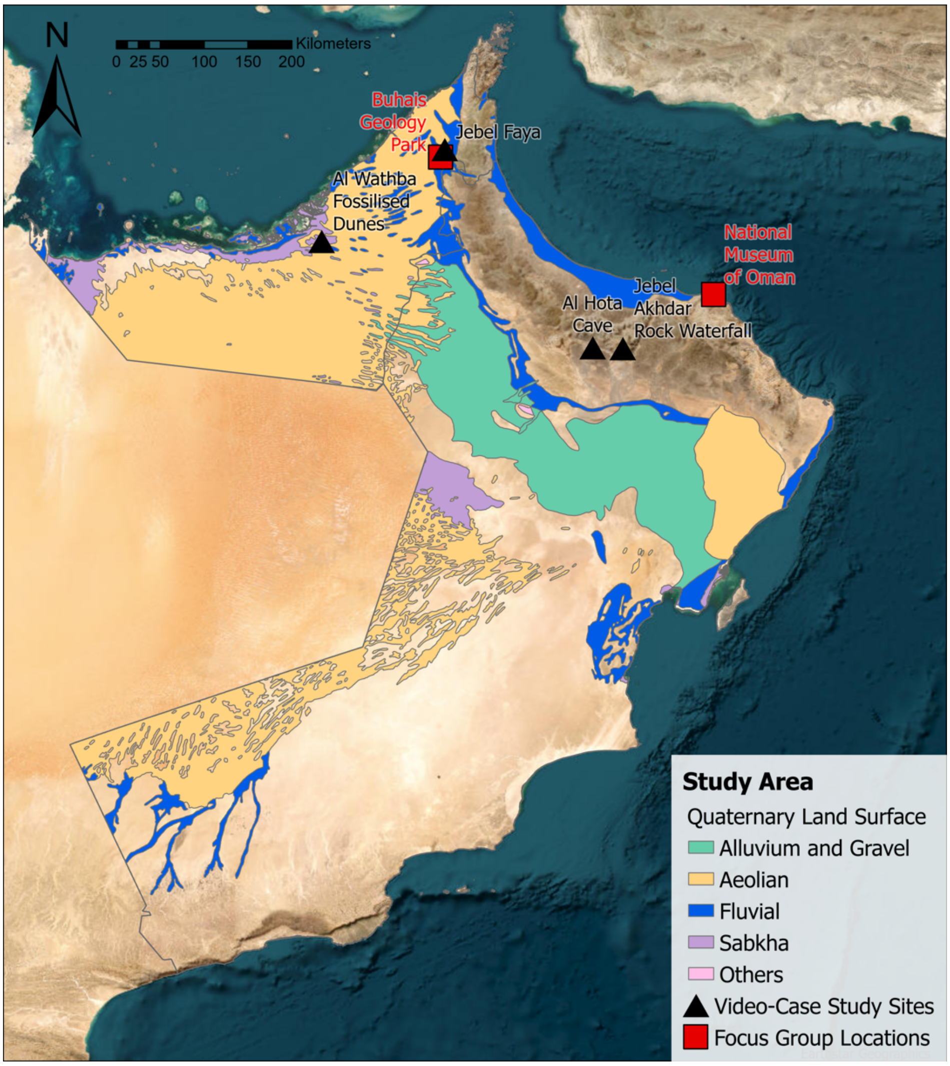

Figure 1: A map of southeast Arabia with Quaternary land surface characteristics, locations of case study sites in the videos, and locations where focus group meetings were conducted. Geological data derived from Pollastro et al. (1999)

3 Methodology

To conduct a study on Quaternary geoheritage sites in southeast Arabia using carefully produced videos that align with the audience's needs and expectations, a three-phase approach was formulated and executed. Table 1 summarises the definition of terms as used in this study. The study was conducted between November 2022 to January 2024, as illustrated in Fig. 2. Phase 1 (Section 3.1) involved focus group meetings to identify suitable contents for the videos, Phase 2 (Section 3.2) covered the production of the two videos, and Phase 3 (Sections

3.3–3.4) consisted of the online experiment and data analysis. Phase 3 involved three survey waves with random assignment to treatment and control groups after Wave 1.

Table 1 Key terms and definitions used in this study.

Term	Definition (as used in this study)
Wave	A round of survey data collection in a longitudinal study design; in this study, the same participants who answered a wave of questionnaire were recontacted to participate in the subsequent wave. (i.e. Wave 1: pre-video, Wave 2: post-video, Wave 3: three-month follow-up).
Treatment group	Participants who viewed the video incorporating geocultural context.
Control group	Participants who viewed the video focusing solely on Quaternary science.
Random assignment	Allocation of participants to treatment or control groups by chance after completion of the pre-video survey.
Difference-in-differences (DiD) analysis	A statistical approach comparing changes over time between treatment and control groups to estimate the effect of the intervention (further detailed in Section 3.4).
Confidence Interval (CI)	A standard statistical measurement used to illustrate the range of uncertainty around a statistical result, such as those from Differences-in-Differences analyses. The true value of the effect being assessed falls between the upper and lower bounds of this confidence interval with 95% certainty.
Specialist	Participant with formal training in geoscience (students or professionals).
Non-specialist	Participant without formal training in geoscience.
Knowledge test questions	Structured test questions used to assess recognition and understanding of concepts presented in the videos.
Attrition	Reduction in the number of participants completing successive survey waves.
Self-reported knowledge	Participants' subjective assessment of how much they feel they know about a topic.

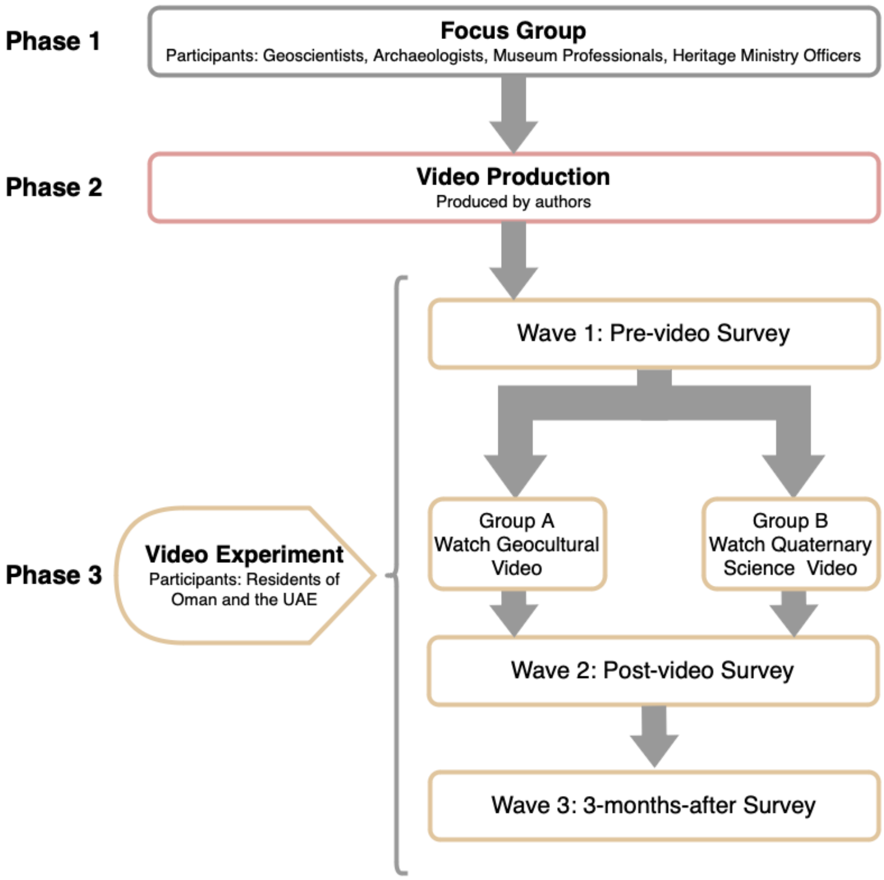

Figure 2 Flow chart describing the phases of the study

3.1 Phase 1: Focus Group to identify video contents

To determine the content of the videos, including the optimal use of the geocultural connections, two focus group meetings were conducted, once in the UAE and another in Oman. Key partners and decision makers involved in the protection and communication of Quaternary sites, including museum professionals, geoscientists, archaeologists, and officials from the Ministry of Heritage, were invited to participate. The participants (n=5 in the UAE, n=7 in Oman) were provided with a brief presentation by the authors on the focus of this study, followed by descriptions of the relationship between archaeology, culture, and the palaeoenvironment. Subsequently, the participants engaged in a discussion on three main topics: their reaction to the presentation, recommendations based on past experiences, and identification of the main factors to be emphasised in the videos. The focus group meetings were designed to last approximately one hour and half to two hours each. At the beginning of each focus group meeting, the facilitators explained that the videos would target adults living in Oman and the UAE with or without interest in geoheritage sites. Participants were asked to suggest themes, examples, and narrative approaches that they think would be engaging for this audience. Key themes emerged in these focus groups directly informed the video scripts and the selection of example sites described in Section 3.2. Considering the linguistic abilities of the participants, the focus group meeting in Oman was conducted in English with Arabic interpretation available upon request, while the focus group meeting in the UAE was conducted in both English and Arabic, facilitated by an interpreter. The discussions in the focus group meetings were recorded, transcribed, coded, and analysed qualitatively using deductive and inductive content analysis (Bengtsson, 2016) via NVivo to find categories and themes relevant for the research questions.

3.2 Phase 2: Video Production

Based on the insights gained from the focus group discussions, two videos were developed by the authors in collaboration with partners. The videos incorporated footage filmed by the authors, as well as videos and photographs provided by collaborators, along with Creative Commons licensed visuals and music. Each video featured voice narration in English, complemented by dialogues with experts conducted in Arabic, with corresponding translation provided as subtitles in Arabic or in English. The videos were carefully crafted to maintain a similar length, with the primary distinction between the two being an emphasis on the geocultural context in one (referred to as the geocultural or treatment video), and the exclusion of the geocultural context in favour of a more detailed description of the Quaternary science in the other (Quaternary science or control video).

3.3 Phase 3: Video experiment

In phase 3, an online experiment was conducted using the videos produced in the second phase. Participants were recruited based on the inclusion criterion of being residents of the UAE or Oman. Recruitment efforts included calls at universities, as well as emails and posts through nature societies, museums, and social media platforms. The experiment consisted of a registration process and three waves of surveys, including a questionnaire administered before, immediately after, and three months after watching the video. As described in Table 2, in total, 211 individuals registered their interest in the study, 160 completed the pre-video questionnaire (Wave 1), 104 completed the post-video questionnaire (Wave 2), and 82 completed the three-months-after questionnaire (Wave 3). For the purposes of the experiment, participants were divided into two groups: Group A (the treatment group), who watched the geocultural video, and Group B (the control group), who watched the Quaternary science video.

Table 2 Participant numbers across survey waves in phase 3 of the study

Stage	Total	Group A (Geocultural video/Treatment)	Group B (Quaternary Science Video/Control)
Registered interest	211	Not yet assigned	Not yet assigned
Wave 1 (pre-video survey)	160	Not yet assigned	Not yet assigned
Wave 2 (post-video survey)	104	49	55
Wave 3 (3-months-after survey)	82	38	44

Upon completion of the pre-video questionnaire, participants were randomly assigned to either Group A or Group B. All procedures of the experiment were conducted using online questionnaires (see Supplement i), and the survey was available in both Arabic and English. The questionnaire was first prepared in English and then translated into Arabic by one of the authors (H. Al Rawahi), a native Arabic speaker and a geoscientist. The differences of the two language versions were reviewed and considered negligible in analysing the answers. To enable longitudinal follow-up across the three survey waves, participants were asked as optional questions to provide their name, email address, WhatsApp contact, and institutional affiliation. These personal data were stored separately from the survey responses and were used only to contact participants about subsequent questionnaires. For analysis, each participant was assigned an anonymised code, and no personally identifiable information was included in the analytical dataset; the procedures followed the ethical approval described in the Ethics statement section.

The three questionnaires aimed to assess the participants' knowledge and interest in geoheritage sites, Quaternary geoheritage sites, archaeological sites, and the relationship between Quaternary geoheritage sites and archaeological sites. The Quaternary geoheritage section included two sets of knowledge test questions: one in which participants were asked to select photos of Quaternary geoheritage sites from a set of photos, and another in which they chose photos corresponding to geocultural elements at those sites (see Supplement i for full question wording). Both knowledge test questions were presented as multiple-choice questions with multiple correct and incorrect answers. Wave 1 additionally included questions about participants' level of knowledge and interest in natural heritage sites to gauge their predisposition towards nature and nature conservation. After participants answered the questionnaire of Wave 2, a list of additional resources was sent to them to learn more about geoheritage sites and sites that were featured in the video. In Wave 3, additional questions were included to assess participants' impressions of the video and its impact.

Each questionnaire was designed to take between 5–10 minutes to complete. Most questions utilised a five-point Likert-like scale, in which higher values reflect higher levels of agreement, interest, or perceived importance, with exceptions including Yes/No questions, text-entry questions (mostly in Wave 3 regarding impressions and impact of videos), multiple-answer questions (including knowledge test questions), and questions on the importance of protecting certain types of sites, which were presented as a 10-point slider-scale. Text-entry questions were included to assess participants' recollection of Quaternary geoheritage sites. The full questionnaires are available in Supplement i.

3.4 Data analysis

The data collected from the questionnaires underwent quantitative and qualitative analysis, based on the nature of the questions. The statistical analyses were conducted using paired t-tests and difference in differences analysis. Although some discussion continues on the treatment of aggregated Likert-type data as an ordinal scale rather than discrete categories (Bishop & Herron, 2015), this study employed parametric methods to analyse this data in line with other studies such as De Winter and Dodou (2010).

To text-entry questions, a qualitative assessment was conducted for responses. The qualitative analysis involved deductive and inductive content analysis using NVivo to categorise themes related to the research questions and emerging themes from the responses. The predetermined themes used for the deductive content analysis included those related to the key points mentioned in the focus groups, and options indicated in the questionnaire as multiple-choice questions.

Statistical analyses followed methods commonly used in Randomly Controlled Trial (RCT) experiments, where both treatment and control groups are present. In this study, both groups viewed a video about Quaternary geoheritage sites, with the control group watching a video focused solely on Quaternary science and the treatment group watched a video with geocultural information included. While a third control group watching an unrelated video would have been ideal, practical constraints in respondent recruitment limited this option. However, the absence of a true "baseline" control group did not hinder the effects of the treatment –i.e., the inclusion of geocultural information in the video. Since the members of the control group had also watched a relevant video and we would expect it to have an effect on their responses in the post-treatment (Wave 2) and follow-up (Wave 3) surveys, it was determined that the most appropriate method for analysing this data would be a difference-in-differences (DiD) analysis with fixed effects for the treatment group and the survey wave. DiD analysis is a specific type of fixed effect analysis that is commonly used to evaluate treatment effects in natural experiments (see Abadie (2005) for a detailed discussion). It allows for the assessment of treatment effects over time, even when there are underlying differences between observed groups and timeframes. In practical terms, this approach compares how much participants' responses changed over time in the treatment group with how much they changed in the control group, thereby isolating the effect of including geocultural information in the video.

For each survey question, all responses in each wave of the survey were initially compared to the Wave 1 responses using a t-test to determine if there was a statistically significant difference between waves.

Subsequently, DiD was conducted, using only the data set of participants who completed all three waves of questionnaire (n=82), to assess the effects of the treatment. It is important to note that even in cases where the t-test for the overall dataset showed no statistical significance, the DiD analysis could reveal a significant difference between treatment and control groups. This is because the treatment group may have a positive effect while the control group has a negative effect, potentially cancelling each other out in the overall population analysis.

When applied to samples of the size used in this study, estimates of treatment effects are necessarily accompanied by substantial statistical uncertainty. With 82 complete cases, the study is underpowered to reliably detect small effects, particularly under inference procedures that account for within-respondent dependence over time. We therefore emphasize effect-size estimates and uncertainty intervals by reporting 95% confidence intervals (CIs) for our DiD analyses, rather than relying on dichotomous significance thresholds. Confidence intervals allow interpretation of the range of plausible directions and magnitudes for the true effect sizes, which is more informative for these data than significance-level reporting alone. For example, in cases where confidence intervals are narrow and centred near zero, we can rule out the presence of large treatment effects even when results are not statistically significant in the conventional sense. Across outcomes, many estimates remain imprecise, and we interpret findings in light of this uncertainty as reflected in the reported confidence intervals.

Finally, the data were subdivided into specialist and non-specialist respondents. The specialist group comprised of respondents who were either geology students or professionals in a geology-related field, while the non-specialist group comprised all other respondents. This division aimed to examine whether the treatment effect varied based on the respondent's level of expertise or prior subject knowledge. The DiD analysis was then re-run for both groups, and the results were used to conduct direct comparisons of the treatment effect between specialist and non-specialist respondents.

4 Results and Discussion

4.1 Phase 1

Focus group meetings were conducted in November 2022 at Buhais Geology Park (UAE), and in December 2022 at the Oman National Museum. As shown in Table 3, participants in the UAE included an archaeologist, two staff members from a geology museum, and two staff from an archaeology museum. The Oman focus group comprised two archaeologists, two geologists, two National Museum staff, and one officer from the Ministry of Heritage. Participants were purposefully selected to include specialists in various relevant disciplines, both genders and a mix of nationals and non-nationals to ensure diversity of expertise and perspectives.

Table 3 Participant profile for the focus group meetings conducted in this study

	Participants	Number	Non-nationals
UAE	Archaeologist	1	1
	Staff from Buhais Geology Park	2	0
	Staff from Mleiha Archaeology Center	2	2
Oman	Archaeologist	2	1
	Geologist	2	0

Staff from the National Museum of Oman	2	0
Staff from Ministry of Heritage	1	0

The discussions lasted approximately two hours in the UAE and 1.5 hours in Oman. Analysis of the coded transcripts identified seven main themes, discussed below. Overall, participants emphasised the need to balance visual appeal, scientific rigor, and cultural relevance when designing a video to communicate Quaternary geoheritage. Constructing a cultural narrative was seen as essential for sustaining engagement and enhancing understanding among non-specialist audiences.

4.1.1 Visual Preference

Participants consistently favoured visually striking imagery over highly technical scientific visuals, particularly to attract non-specialist viewers. In the UAE, there was additional support for using scientific images that also demonstrate aesthetic qualities. Visuals were regarded as critical for capturing initial attention, particularly among non-specialists. One participant aptly summarised this sentiment, stating “for me it's the image from the first glance, you can decide whether you will like it or not like it. You are interested, you will go further, or you withdraw.” Participants also recognised the importance of scientific imagery when used selectively to explain key processes and values beyond their aesthetic beauty. Overall, participants advocated for a balanced visual strategy that combines aesthetic appeal with descriptive/explanatory content.

4.1.2 Financial Matters

Opinions differed regarding the inclusion of economic benefits associated with protecting Quaternary sites. UAE participants advised against emphasising economic value in a public-facing video, despite acknowledging its importance. In contrast, most participants in Oman supported its inclusion, provided it did not dominate the narrative. Across both groups, there was an agreement that economic aspects can enhance relatability, particularly for local communities, but should be introduced sparingly and without overshadowing other content.

4.1.3 Need to Raise Awareness

All participants strongly supported the need to raise awareness of Quaternary geoheritage, citing widespread public unfamiliarity with its significance. Clear, accessible communication with minimal technical jargon was considered essential. At the same time, participants stressed the importance of articulating the purpose of awareness raising, noting: “the question that we always forget is, why do we want people to be aware of those sites, maybe it's actually good for them not to be aware of this kind of stuff.” A clear message describing relevance to the audience must be explicit to justify engagement with the topic.

4.1.4 Narrative

There was unanimous agreement on the importance of a strong narrative. Two complementary approaches were identified: narratives that encourage audiences to imagine past environments, and those that draw on geocultural contexts to foster personal connections. Suggestions included incorporating culturally resonating elements, such as references to historical climate change in religious or literary traditions, to enhance engagement and comprehension.

4.1.5 Local People, Culture, and Knowledge

Participants strongly supported integrating cultural identity into the video, particularly through storytelling by respected local figures. Many noted that community connections significantly influence perceptions of a site’s value. Religious relevance was also unanimously endorsed as an effective means of engagement. Notably, support for cultural connections was expressed by both nationals and non-national participants, with enthusiastic endorsement from the latter.

In Oman, participants emphasised that while foreign researchers are acceptable narrators, local voices are preferable when possible. They also generally supported the use of interviews as a means of adding authority and personal connection. However, participants in the UAE expressed concern that interviews could make the video feel overly didactic. The prevailing view was that, if used, interviews should be brief and limited.

4.1.6 Scientific Information

While some participants initially identified scientific content as the most important element, all agreed that the video should communicate the scientific significance of each site in a general, rather than a specific, sense. However, opinions varied regarding the appropriate level of detail. Most participants favoured presenting simplified explanations rather than detailed scientific data, particularly for non-specialists.

4.1.7 Sequence of Presentation

Participants agreed that videos should begin with visually engaging imagery to capture attention, followed by a simple explanation of geoheritage concepts. Interviews, if included, were generally discouraged at the opening stage. There was consensus that images must be accompanied by clear explanatory context to ensure meaning. In Oman, participants proposed highlighting the uniqueness of regional Quaternary geoheritage early in the video. Cultural, economic connections were seen as effective engagement tools, Nevertheless, deeper discussions of scientific, cultural, and economic significance were identified as elements best introduced once viewers had developed a basic understanding of geoheritage and Quaternary geoheritage. Case studies were supported by many participants, though some in the UAE considered them of limited importance.

4.1.8 Summary of Focus Group Recommendations

The focus group meetings underscored the importance of cultural connection in communicating Quaternary geoheritage and identified the following recommendations for video design.

- Begin with visually engaging footage and familiar sites before introducing technical Quaternary elements
- Structure content progressively from general overview to more detailed explanation
- Incorporate archaeological, cultural, and religious narratives where appropriate
- Use an accessible, conversational tone supported by locally grounded perspectives
- Frame geoheritage in relation to everyday values, such as natural beauty, cultural relevance, and conservation needs

4.2 Phase 2

Two videos were produced based on established best practices in science communication and insights gained from the focus group discussions. The videos were created specifically for this research project and are not intended to function as comprehensive museum or geopark interpretation tools. The videos are available online (Control Video: https://ora.ox.ac.uk/objects/uuid:e14384cb-68fa-45f1-914d-3204e05bb3ea, Treatment Video:

https://ora.ox.ac.uk/objects/uuid:ee8c3f2a-1888-4967-a104-b5799ba68d8d), and their structure and duration are summarised in Table 4.

Table 4 Contents and duration of the two videos produced for the study. Contents with one asterisk indicate sections with different narration/dialogue between the two videos and contents with two asterisks indicate sections where cultural content is inserted

	Geocultural video (seconds)	Quaternary Science Video (seconds)
Introduction	30	36
Introduction of narrator and title	22	22
Geoheritage sites–Global	17	17
Geoheritage sites–SE Arabia	29	31
History–Earth's geology	12	14
Introduction to Quaternary geoheritage (scenery)	16	18
Introduction to Quaternary period (scientific)	11	15
Examples of Quaternary sites in SE Arabia	15	15
Social relevance of Quaternary sites for geohazards	14	16
Quaternary climate change*	39	47
Implications for the Quran**	30	0
Archaeological relevance**	38	0
Example 1, travertine–non-cultural* (dialogue in Arabic)	31	52
Example 1, travertine–cultural** (dialogue in Arabic)	8	0
Geoheritage conservation frameworks and geotourism (economic relevance)	30	34
Example 2, fossilised dunes** (dialogue in Arabic)	31	46
Example 3, Al Hoota Cave	32	36
Example 4, Jebel Faya–non-cultural*	18	77
Example 4, Jebel Faya–cultural**	64	0
Endangerment of Quaternary sites	19	19
Summary	33	35
End credit	6	6
Total duration	545	536

The total duration of the geocultural video was 9 minutes 5 seconds (545 s), compared with 8 minutes 56 seconds (536 s) for the Quaternary science video. Both fall at the upper end of the 6–9 minute duration range recommended in the literature for optimal audience engagement. Length differences were minimised by extending transitional sequences in the Quaternary science video, which contained 153 fewer words (English translation) than the geocultural video. Geocultural content was accounted for 140 seconds (approximately 26%) of the geocultural video. These elements included: (i) a discussion linking Quaternary palaeoenvironmental evidence with a verse in the Quran, (ii) an introduction to the relevance of Quaternary science for archaeology, and (iii) culturally grounded interpretations at example sites through agricultural and archaeological contexts. In contrast, the Quaternary science video incorporated additional scientific detail, including explanations of site formation processes and sedimentary cross-sections at selected examples. Neither video employed formal interviews, however, both included short dialogue segments with local geologists at one site in Oman (example 1) and one in the UAE (example 2), providing site-specific explanations. Four sites were featured, selected to represent a range of Quaternary environments in southeast Arabia (travertine, coastal dunes, cave systems, and a geocultural landscape). Selection criteria included the availability of well-documented Quaternary research, representation of diverse environments, and a mix of protected and unprotected sites.

Prior to distribution, both videos were piloted and reviewed by focus group participants to ensure scientific accuracy and appropriate representation of cultural and social content.

4.3 Phase 3

4.3.1 Participant Profile

After excluding blank responses and those not meeting the inclusion criteria, the study recorded 160 valid responses in Wave 1 (pre-video), 104 in Wave 2 (post-video), and 82 in Wave 3 (3-months-after). Participant characteristics are summarised in Tables 1 and 5. Drop-out rates were within or better than the expected range of 30–40% for longitudinal studies (Grønmo, 2019), with a particularly low drop-out rate of 21% between Waves 2 and 3. The majority of statistical analyses conducted on the data use the sample of 82 respondents who completed all three waves (in particular, this is the base sample for Difference in Differences analysis). Basic descriptive statistics and t-tests of Wave 2 reported below are based on 104 participants who completed surveys up to that point. Given the total population of southeast Arabia at 14.1 million, according to Yamane's formula for sample size (Yamane, 1967), 104 participants represent the population of this region at a margin of error at ±9.8%, while 82 participants have a ±10.9% margin. While smaller than the sample required for a ±5% margin, this size was considered adequate for exploratory analysis, especially given the strong caveat that the study focused on a specific – and much smaller – population of university students and subject specialists.

Table 5 Breakdown of video study participants. All questions in the survey were optional, leading to some missing responses.

Research Stage		Total	Specialist	Non specialist	Student	Non student	UAE resident	Oman resident	National	Non national
Wave 1		160	73	87	109	51	64	94	128	31
Wave 2	Control	49	26	23	40	9	16	33	39	10
	Treatment	55	22	33	39	16	24	31	43	12
Wave 3	Control	38	22	16	33	5	27	11	31	7

Treatment	44	19	25	33	11	18	26	33	11

Participants were drawn from both Oman (n = 64) and the UAE (n = 40), with nationalities comprising 61 Omanis, 21 Emiratis, and 22 non-nationals. Although nationals were overrepresented relative to national demographics, comparative analyses revealed no statistically significant differences between national and non-national participants; these results are of limited value due to the low statistical power of the dataset when subdivided in this way, and therefore are not presented.

The majority of participants were university students (n = 78), including 47 studying geosciences and 31 studying other disciplines. Of the 23 employed participants, only one worked in geology-related field. Participants who are geoscience students or professionals were classified as domain specialists (n=48) and the rest were categorised as non-specialists (n=56). Specialists were significantly more likely to report prior awareness of geoheritage sites (t-test p <0.001) or Quaternary geoheritage sites (t-test p=0.051 in Chi-squared test and p-value=0.035 in Fisher's exact test). Many specialists knew some geoheritage sites (95%), but only half of them (50%) could recognise or identify recognition of Quaternary geoheritage sites.

Participants of this study, regardless of their demographics, expressed strong pro-conservation attitudes prior to viewing the videos, with high rating of the importance of protecting natural heritage (mean = 9.2/10, SD=1.4. Support was similarly strong for geoheritage sites (mean=9.0, SD=1.7) and Quaternary geoheritage sites (mean=8.6, SD=2.0), although increasing specificity was associated with greater variability in responses.

While this study aimed to target the general public, the final sample was skewed towards a young, highly educated, and environmentally engaged demographic. This profile aligns with audiences commonly identified as potential geotourism participants in previous studies (Dowling & Allan, 2018; Kim et al., 2008; Štrba, 2019).

4.3.2 Impressions and impact of the video after 3-months

Wave 3 responses indicated positive and sustained impressions of both videos. Approximately half of participants in each group reported watching the video more than twice. Self-reported recall of content was higher in the treatment group (25%) than in the control group (16%).

Most participants (80%) considered the video length appropriate, although 17% felt it was slightly too long. This perception was more common in the control group (24%) than in the treatment group (13%). Regarding impact, 91% of respondents reported increased interest in Quaternary geoheritage, with a slightly higher proportion in the treatment group, though differences were not statistically significant. An unexpected finding concerned the aspects that left the strongest impression. Treatment participants most frequently pointed to the importance of protecting geoheritage, whereas control participants most often cited connections between Quaternary geology and culture or archaeology, despite these not being explicitly addressed in the control video. This may reflect independent follow-up learning or implicit cultural interpretation by viewers. Overall, these findings suggest that the geocultural framing may have oriented treatment viewers towards broader conservation values rather than specific thematic elements.

4.3.3 Qualitative analysis on impressions toward the video

Of the 82 Wave 3 respondents, 46 provided open-ended feedback. The responses consisted of 20 answers from the treatment group and 26 from the control group. Frequently cited positive aspects included learning outcomes (13), clarity of presentation (8), and beautiful scenery (8). Participants described the videos as accessible, clear, and engaging, and several highlighted the dialogue with local geologists as particularly effective. In contrast, only a small number of comments explicitly referenced Quaternary geoheritage sites (6), as opposed to general geoheritage sites (19) suggesting that while the videos effectively conveyed general geoheritage concepts, and Quaternary specificity may have been less salient.

Suggestions for improvement (33 open ended answers) were provided by 20 respondents, most commonly recommending a shorter duration, predominantly from control group participants. Conversely, several treatment group participants suggested including additional content to further expand their knowledge. Other themes included the production value, including the adding of a short animation (2), improving the narration (2), and improving the overall quality (3) as well as the delivery of the contents by providing less complexity (3), and making the content more interesting (5).

Overall, qualitative findings reinforce the quantitative results, indicating stronger engagement and tolerance for video length in the treatment group. Feedback also validated several focus group recommendations, particularly regarding clear language, aesthetic visuals, and the inclusion of local voices.

4.3.4 Statistical Analysis

Statistical analysis of the questionnaire answers focused on the questions pertinent to Quaternary geoheritage sites and the geocultural context. The results of the seven target questions are shown in Fig. 3 and Table 6 and analysed further in the following sections. The detailed statistical figures for the DiD analysis can be found in Supplement ii.

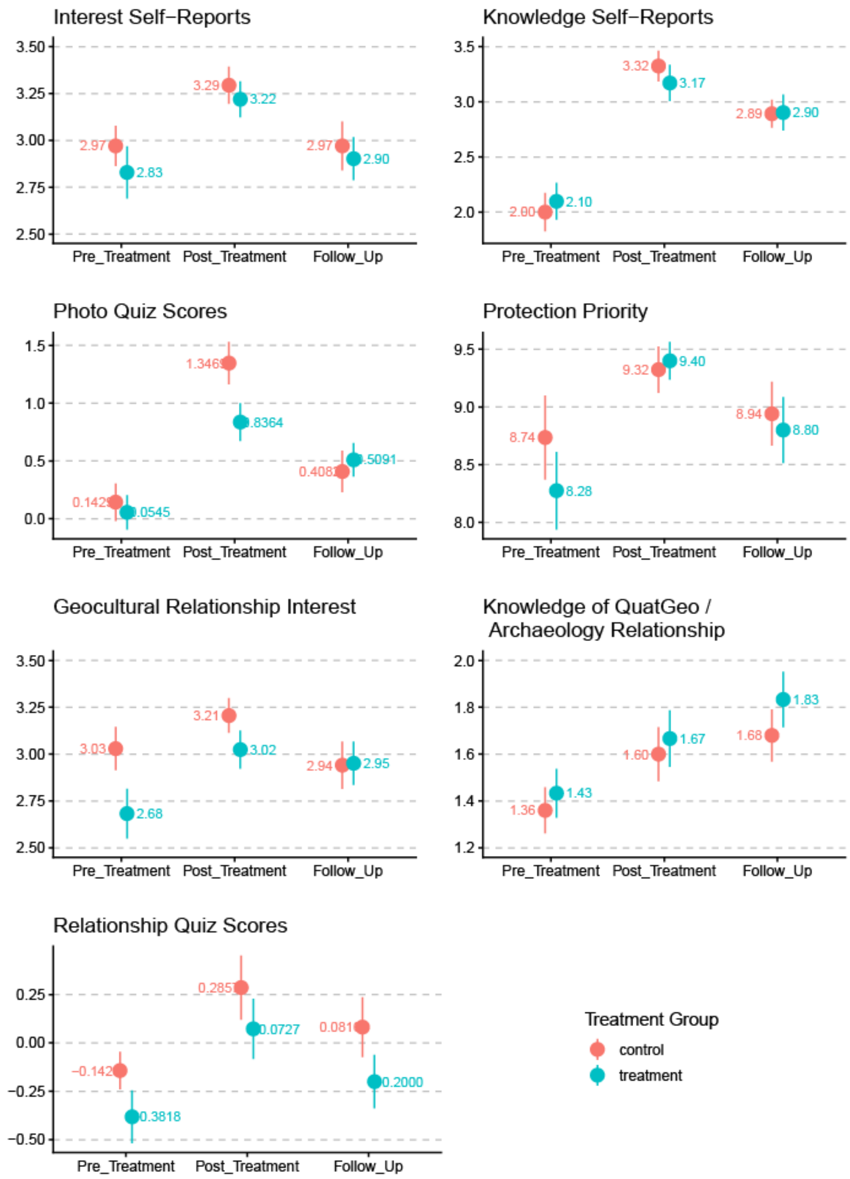

Figure 3 Changes in questionnaire scores between three waves of questionnaires, disaggregated by treatment group

Table 6 Summary of DiD results

Category	Scale	DiD Coefficient					
		Post-video [95% confidence interval]			3-month follow-up [95% confidence interval]		
		All participants	specialists	non-specialists	All participants	specialists	non-specialists
Interest in learning about Quaternary geoheritage	Five-point scale (0–4)	0.067 [-0.302, 0.436]	0.056 [-0.519, 0.630]	0.003 [-0.441, 0.447]	0.073 [-0.282, 0.429]	-0.056 [-0.611, 0.500]	0.155 [-0.310, 0.620]

Self-reported knowledge: Quaternary geoheritage	Five-point scale (1–5)	-0.251 [-0.738, 0.235]	-0.302 [-1.115, 0.512]	-0.106 [-0.689, 0.477]	-0.087 [-0.637, 0.463]	-0.222 [-1.029, 0.585]	-0.101 [-0.848, 0.647]
Photo knowledge test (identifying Quaternary sites)	Score (correct-incorrect)	-0.197 [-0.740, 0.347]	-0.467 [-1.324, 0.391]	0.019 [-0.764, 0.901]	0.016 [-0.518, 0.551]	-0.006 [-0.852, 0.841]	-0.075 [-0.763, 0.801]
Protection priority for Quaternary geoheritage sites	Ten-point scale (1–10)	0.537 [-0.375, 1.448]	0.227 [-0.995, 1.449]	0.517 [-0.785, 1.818]	0.319 [-0.613, 1.251]	0.197 [-1.111, 1.505]	0.308 [-1.043, 1.660]
Interest in Quaternary geology-archaeology relationship	Ten-point scale (0–4)	0.165 [-0.191, 0.520]	0.067 [-0.479, 0.612]	0.193 [-0.279, 0.664]	0.357 [0.004, 0.709]	0.167 [-0.277, 0.610]	0.562 [-0.046, 1.170]
Self-reported knowledge: geocultural relationship	Five-point scale (1–5)	-0.007 [-0.318, 0.305]	-0.091 [-0.533, 0.352]	0.011 [-0.410, 0.432]	0.08 [-0.254, 0.414]	0 [-0.665, 0.665]	0.135 [-0.248, 0.519]
Geocultural knowledge test (relationship examples)	Score (correct-incorrect)	0.037 [-0.635, 0.708]	-0.150 [-1.265, 0.965]	0.280 [-0.625, 1.184]	-0.157 [-0.791, 0.477]	-0.294 [-1.281, 0.692]	0.038 [-0.869, 0.956]

4.3.4.1 Self-Reported Interest and Knowledge in Quaternary Geoheritage

Building on the overall patterns shown in Fig. 3 and Table 6, the first set of outcomes concerns respondents' response to five-point scale answers to self-report *interest* in learning about Quaternary geoheritage (0= no interest to 4= very interested) and perceived *knowledge* of Quaternary geoheritage sites (1 = very little knowledge to 5 = very high knowledge). Interest increased significantly immediately after viewing (t-test $p = 0.0011$), but this uplift was not evident at the three-month follow-up when comparing pre-video and follow-up distributions (t-test $p = 0.55$). Perceived knowledge, by contrast, increased strongly in the post-treatment survey (t-test $p < 0.001$) and remained significantly higher than baseline at follow-up (t-test $p < 0.001$), despite some degree of regression towards the mean.

Comparative analysis adds nuance to these patterns. For *interest*, DiD coefficients were generally small with confidence intervals around zero, effectively ruling out large effects, with the main exception being a possible small positive effect among non-specialists at follow-up (0.155, 95% CI [-0.310, 0.620]), albeit with substantial uncertainty. Corroborated by the qualitative evidence suggesting more favourable opinions towards the treatment video, this suggests that the geocultural framing may have helped non-specialists maintain interest over time, even when the population-level effect diminished. This finding contrasts somewhat qualitative responses, in which we observed a self-reported gain in interest towards Quaternary geoheritage sites in Wave 3. One plausible explanation for this discrepancy could be the difference in wording of the questions, between a sense of overall interest in the topic and the interest in learning about the Quaternary geoheritage sites. While participants may have experienced a general uptick in interest, it may not necessarily have translated into a desire to delve deeper into Quaternary geoheritage sites.

For perceived knowledge, however, DiD analysis comparing treatment and control groups suggested a negative effect associated with assignment to the treatment group after Wave 2 for both specialists and non-specialists, which dissipates by Wave 3. This result indicates that participants in the control group reported larger increases in perceived knowledge, which could possibly be explained by differences in content focus. The treatment video introduced a broader range of themes, potentially leading viewers to feel less confident about their specific knowledge of Quaternary geoheritage, whereas the more narrowly focused control video provided detailed scientific explanations (e.g. stratigraphic cross-sections) that may have enhanced participants' perceptions of subject-specific expertise.

When comparing specialists and non-specialists in terms of perceived knowledge in Wave 2, specialists reported a greater increase than non-specialists (mean rising from 2.36 to 3.74 for specialists, compared to 1.74 to 2.74 for non-specialists). This pattern aligns with established findings in geoscience education and communication literature, which suggest that individuals without prior training often find geological concepts, particularly those related to deep time, challenging to engage with (Trend, 1998, 2001), resulting in high barriers to initial learning (Rogers et al., 2024).

These findings indicate that the two videos perform differently across self-reported outcomes on Quaternary geoheritage sites. The control video generated larger immediate increases in perceived knowledge, while the treatment video shows some potential to better sustain interest among non-specialists over time. Altogether, the advantage of the geocultural context points to maintaining engagement over time, rather than providing a stronger sense of knowledge gain.

4.3.4.2 Photo Knowledge Test Question Scores for Quaternary Geoheritage Sites

Participants were asked to complete a photo-based knowledge test question in which they identified images they believed to be Quaternary sites. The photos used for this knowledge test question is shown on Fig. 4. Five photographs were provided, of which three were correct and two incorrect. The score for this question was calculated by subtracting the number of incorrect selections from the number of correct selections. This method was chosen to reduce bias arising from indiscriminate multiple selections, which could skew apparent knowledge levels. Analysis revealed a highly significant increase in quiz scores immediately after video viewing (t-test $p < 0.001$). While a substantial degree of mean reversion was observed by the time of the follow-up survey, scores remained significantly higher than the pre-video scores (t-test $p = 0.013$), indicating that the videos successfully embedded knowledge to the participants for at least several months.

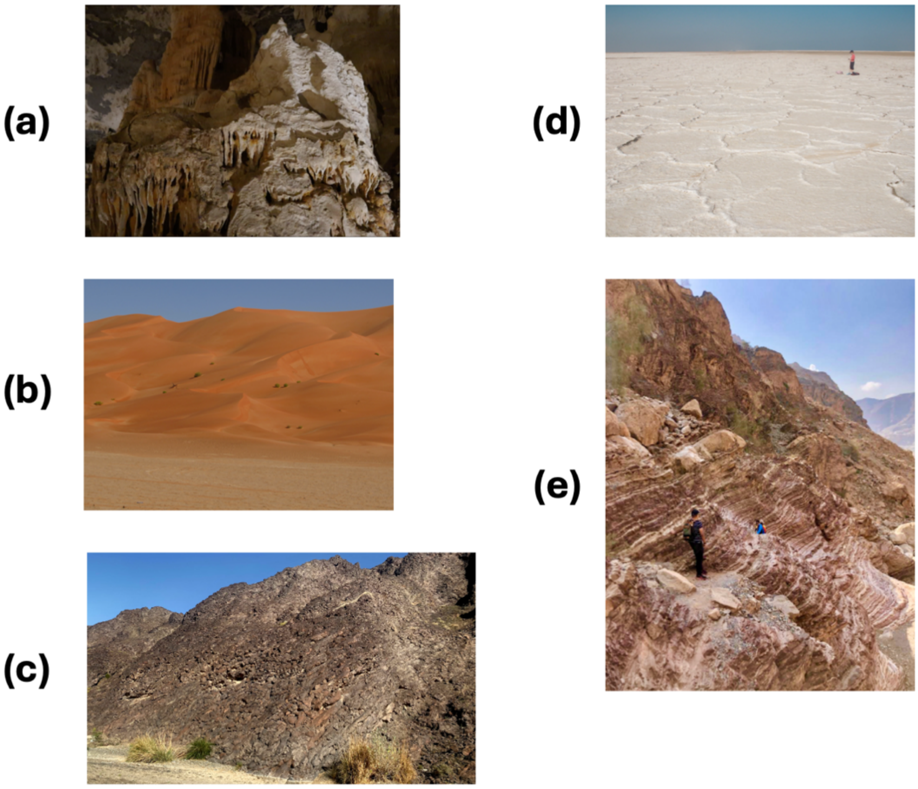

Figure 4 Photos used in the knowledge test to identify Quaternary geoheritage sites. The correct answers are (a) [cave features], (b) [sand dunes] and (d) [sabkha]

The DiD analysis provided a clearer picture behind these trends. Immediately after viewing the videos, the results for the treatment group suggest smaller improvements than the control group. However, by the follow-up survey, this difference was negligible. Although the control group outperformed the treatment group in the immediate post-video survey, after three months the two groups performed almost the same. The control video's focused and in-depth information approach appears to have facilitated better short-term identification of Quaternary geoheritage sites, but after three months, this comparative advantage seems to have been lost, leading to a similar performance by both groups.

When separating the participants into expertise level, it is clear that the initial better performance by the control group was driven entirely by specialist respondents. While non-specialists in the treatment group performed no differently from their control counterparts immediately after viewing, the specialists in the treatment group performed worse. This could be explained by the control video including a more scientific details of Quaternary sites, that participants with domain knowledge could apply in this question immediately after watching the video. However, this immediate effect did not last until the follow-up phase, ultimately leading to the two videos having similar effects as tools for teaching. This suggests that the geocultural framing did not provide advantages for people's learning outcomes through a short video, but also showed that it did not hinder or dilute the learning experience in the medium-term, despite including les scientific details.

4.3.4.3 Protection Priority for Quaternary Geoheritage Sites

Participants were asked to rate the importance of protecting Quaternary geoheritage sites on a 10-point scale (1 = not important to 10 = top priority). A statistically significant increase in protection was observed immediately after viewing the videos (t-test $p < 0.001$). Although scores exhibited a high degree of regression towards the mean by the follow-up survey, they remained slightly higher than pre-video levels. However, this difference was not statistically significant (t-test $p = 0.142$). It is notable that baseline scores were already high (mean ~ 8.5, with the highest possible rating being 10), and very few respondents rated these sites as a low priority for protection.

DiD analysis suggest that the positive gains in this question were consistently stronger for the treatment group, with greater increases in protection priority than those in the control group overall. This effect was evident immediately after viewing and remained positive in the three-month follow-up survey as well. These findings, albeit tempered by the uncertainty inherent in these statistical results, indicate that the treatment video was more effective in strengthening opinions about the importance of protecting Quaternary geoheritage sites and that these attitudinal changes were sustained over time. This result is consistent with the qualitative findings that the theme of geoheritage protection was the most frequently cited takeaway among treatment-group participants.

The positive effect was particularly strongly indicated for non-specialist respondents with the treatment group in particular. Specialists entered the study with higher baseline scores (a mean value of 9.13 versus 8.23 for non-specialists), which likely constrained the magnitude of observable change due to ceiling effects. Yet, overall, these findings support the conclusion that the geocultural framing employed in the treatment video likely fostered a stronger and more durable sense of importance of conserving Quaternary geoheritage, especially among people who had less prior knowledge of such sites.

4.3.4.4 Overall implications: Quaternary Geoheritage

Taken together, these results demonstrate the effectiveness of video-based communication for enhancing public engagement with Quaternary geoheritage. Both videos increased perceived knowledge and awareness, while the treatment video, in particular, likely exerted a stronger and more persistent influence on attitudes towards conservation. Future research should test these findings among audiences with lower pre-existing interest in nature conservation to assess the broader generalisability of these effects. At the population level, increases in interest in learning about Quaternary geoheritage sites were relatively modest and tended to diminish over time, despite overall improvements in awareness. This suggests that while video interventions can successfully raise awareness, they may not be sufficient on their own to generate sustained motivation for deeper engagement or further learning.

Comparative analysis of the two videos highlights a trade-off between short-term knowledge acquisition and longer-term attitudinal and mnemonic effects. The control video, with its singular and technical focus, likely functioned more effectively as an immediate education resource, producing higher post-video scores. However, after three-months, this comparative advantage is lost, and both groups reported a similar level of knowledge gain. These findings suggest that embedding scientific information within a geocultural narrative may enhance engagement without adverse medium-term effects as a tool for teaching about Quaternary geology.

4.3.4.5 Self-Reported Interest and Knowledge in Relationship between Quaternary Geology and Archaeology

As with the self-reported interest and knowledge in Quaternary geoheritage sites (see 4.3.4.1 above), participants were asked to self-report on a five-point scale about their level of *interest* in learning about (0-4) and *knowledge* on (1-5) the relationship between Quaternary Geology and archaeology. Looking at all participants, interest towards this relationship showed a small but statistically significant increase immediately after viewing (t-test $p = 0.028$), followed by regression towards the mean such that overall interest at follow-up was statistically indistinguishable from baseline. On the other hand, perceived *knowledge* increased significantly immediately after viewing (t-test $p < 0.001$) and remained significantly higher than baseline at follow-up (t-test $p < 0.001$), indicating that participants' perceived understanding of the geocultural relationship continued to develop over time. However, absolute knowledge levels remained low across all survey waves, with mean scores not exceeding 2, corresponding to "not very much" knowledge, demonstrating modest shifts in perceived knowledge rather than substantive mastery.

DiD analysis suggests that the treatment–control contrast was clearer for *interest* than for perceived *knowledge*. For interest, the treatment group showed a notably greater increase than the control group both immediately after viewing the video and three-months after, with the follow-up effect particularly strong (CI lower-end value above 0), indicating a conventionally statistically significant finding, despite the small sample size. The treatment group sustained elevated interest over time while interest among the control group declined to pre-treatment levels, and this effect was more strongly indicated among non-specialists than specialists. This result supports the argument that geocultural framing works well to make Quaternary geoheritage more engaging and digestible for audiences without specialist training. For perceived knowledge, however, DiD analysis revealed very small differences between groups; the only difference that could reasonably be claimed was a small positive impact of the treatment video among non-specialists in the medium term. This may indicate that the geocultural context made a slightly stronger impression among non-specialists, for whom it was both comprehensible and memorable. For specialists, they may have inferred geocultural connections even from the control video, producing only small differences. The overall gain in knowledge reported by the control group, in combination with the qualitative inputs indicating the strong impression of the geocultural element is both interesting and surprising, and may pose a worthy research question for future studies to better understand how this self-reported knowledge gain was achieved.

Taken together, these results indicate that the inclusion of geocultural context was more effective in sustaining interest in the Quaternary geology–archaeology relationship than in producing measurable gains in perceived knowledge. This effect is most clearly expressed among non-specialists, suggesting that geocultural framing may function primarily as an engagement mechanism rather than as a direct instructional tool. While the observed knowledge gains remain modest, the sustained interest among treatment participants highlights the potential of geocultural connections to support longer-term engagement with Quaternary geoheritage topics.

4.3.4.6 Knowledge Test Scores on Relationship between Quaternary Geology and Archaeology

Objective understanding of geocultural connections was assessed through a multiple-choice knowledge test in which participants selected examples of relationships between Quaternary geology and archaeology in southeast Arabia. Of the seven options, three were correct and four were incorrect. Scores were calculated by subtracting the number of incorrect selections from the number of correct selections, in order to reduce bias from indiscriminate responding. Overall scores on this question were extremely low across all survey waves, with mean values hovering around zero. This suggests that the question may have been particularly challenging or that many respondents struggled to grasp this aspect of the material. Nevertheless, a statistically significant improvement was observed immediately after viewing the videos (t-test, $p = 0.0014$). Scores in the follow-up survey were higher than baseline but not significantly so at the 95% confidence level (t-test, $p = 0.109$).

The DiD analysis suggests that, overall, there was little to no difference between the treatment and control groups. A slightly better performance by the non-specialists in the post-video survey could be inferred from the results, but otherwise, the differences were too small to be captured through this study. One possible interpretation is that specialists and non-specialists focused on different elements of the treatment video. Non-specialists may have found the geocultural narrative more relatable and gained immediate knowledge, which could have been too complex to remember after three months. On the other hand, specialists may not have grasped the geocultural framing through a short video.

4.3.4.7 Overall implications: Geocultural Relationship

Overall, these findings highlight that communicating about Quaternary geoheritage sites is more effective at enhancing awareness of geocultural relationships than at generating sustained interest or substantial gains in factual knowledge. Although participants reported increased perceived understanding after viewing the videos, performance on the objective knowledge test was limited. This may reflect the inherent complexity of the topic, the difficulty of the assessment, or constraints associated with using a single question to capture learning outcomes.

Comparative analysis of the two videos suggests that the treatment video's emphasis on geocultural context was particularly effective in stimulating interest, especially among non-specialists, reinforcing the value of geocultural framing as a tool for broadening audience engagement. However, this heightened interest did not translate into improved performance on the knowledge test, and specialists in the treatment group underperformed relative to the control group in some instances. Given the stronger interest and conservation priority gains observed in the study, it appears that the geocultural narrative primarily functioned as a catalyst for curiosity and engagement rather than as a vehicle for conveying detailed factual knowledge. From an outreach perspective, these findings underscore the utility of geocultural context in introducing Quaternary geoheritage to wider audiences, although additional or complementary educational strategies should be provided if the desired outcome is to support deeper learning.

5 Conclusions

This study set out to evaluate the effectiveness of videos, and in particular the role of geocultural context, in communicating the significance of Quaternary geoheritage sites in southeast Arabia. Using a three-phase research design, comprising focus groups to inform video content, video production, and a longitudinal online experiment, the study compared the impacts of two videos: one highlighting the geocultural context and the other focusing solely on Quaternary science. The analysis assessed changes in participants' knowledge, interest, and perceptions related to Quaternary geoheritage sites.

The results provide several important insights into science communication practice and the value of geocultural framing. Contributions from local specialists during the focus group phase underscored the importance of visual appeal, narrative clarity, and culturally relevant storytelling in engaging audiences and facilitating comprehension. These inputs played a central role in shaping videos that were accessible, coherent, and grounded in regional context, demonstrating the value of participatory content development in geoheritage communication.

The experimental comparison revealed that both videos were effective in increasing participants’ awareness of Quaternary geoheritage and strengthening attitudes towards its protection. However, clear differences emerged in how audiences responded over time. The video incorporating geocultural context outperformed the science-focused video in sustaining longer-term interest and fostering a stronger sense of the need for conservation, particularly among non-specialist participants. While the control video functioned more effectively as an immediate educational tool, producing higher short-term knowledge gains, the geocultural video demonstrated superior longer-term outcomes in terms of engagement and attitudinal change. These outcomes were supported in both qualitative and quantitative analyses. Methodologically, these findings highlight the importance of incorporating follow-up measurements in geoscience communication studies, as short-term learning outcomes alone may obscure more durable effects.

Two key advantages of integrating geocultural context into communication strategies for Quaternary geoheritage emerge from this study. First, geocultural framing enhances engagement and accessibility, especially for non-specialists who may otherwise find Quaternary science abstract or difficult to approach. Second, although less effective as a teaching resource, the geocultural approach appears to strengthen pro-conservation attitudes towards Quaternary sites, suggesting its particular value in awareness raising and public engagement contexts rather than formal education alone.

Several limitations should be acknowledged. The sample size of this study was small and skewed towards highly educated, younger participants with pre-existing interest in nature conservation and geoscience. Many respondents were university students or specialists, which likely contributed to high baseline levels of awareness and support for geoheritage protection, potentially amplifying some of the observed effects. Consequently, the findings cannot be directly generalised to the wider population of southeast Arabia or to other sociocultural contexts. Future research involving more diverse demographic groups, lower baseline interest levels, and different regional settings is necessary to test the broader applicability of these results. Further work should also explore how geocultural framing can be combined with complementary educational strategies to support deeper factual learning alongside engagement. Future studies could also examine which elements of the geocultural narrative (e.g., identity-based framing, archaeology, religious narratives) drive interest and opinions on protection.

In conclusion, this study advances understanding of how integrating geocultural connections can enhance science communication efforts aimed at promoting awareness and conservation of Quaternary geoheritage. By leveraging the cultural relevance of these sites in communication strategies, Quaternary scientists and geoheritage practitioners can enhance audience engagement, support sustained interest and inspire longer-term changes in the attitude towards the protection of Quaternary geoheritage sites. These insights offer valuable guidance for refining communication strategies for complex scientific concepts and fostering public engagement with Quaternary science initiatives.

Author contributions

Conceptualisation, K.S., H.V.; Data curation, K.S. H.A.R., R.A.F.; Formal analysis, K.S., R.A.F.; Funding acquisition, K.S.; Investigation, K.S., H.A.R., R.A.F.; Methodology, K.S., R.A.F., H.V., A.G.P.; Project administration, K.S., H.A.R.; Software, R.A.F, K.S.; Supervision, H.V., A.G.P.; Validation, K.S., R.A.F; Visualisation, K.S., R.A.F.; Writing—original draft, K.S.; Writing—review and editing, K.S., R.A.F., H.V., A.G.P. All authors have read and agreed to the published version of the manuscript.

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Ethics statement

This study was approved by the Central University Research Ethics Committee (CUREC) at the University of Oxford to have followed the research protocols set out by the committee with the approval references: SOGE C1A 22 252 and SOGE C1A 23 15.

Conflicts of Interest

The authors declare no conflict of interest regarding this research project.

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