Archaeological and Anthropological Sciences (2025) 17:96
https://doi.org/10.1007/s12520-025-02208-4

RESEARCH

# ‘No easy way from the earth to the stars’: a new statistical approach to the orientation of the Maltese temples

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Received: 5 December 2024 / Accepted: 14 March 2025


**Abstract**

The Maltese Temples, built between 3800 and 2400 BC, are unique structures among the prehistoric monuments of Europe. Their consistent architectural style is characterised by straight entrance corridors leading to open courtyards. This led scholars to ask whether there may have been some intention to orientate their entrances in specific, meaningful ways. Previous attempts to answer this question have either proposed explanations without any formal analysis, only looking to disprove randomness, or have jumped to celestial interpretations without first exploring topographical ones. By contrast, we here deploy a single statistical framework to test the orientation of the Maltese temples against a variety of hypotheses, both terrestrial and celestial. Using a new set of orientation measurements for 32 structures (the largest sample ever analysed) the statistical analysis indicates that despite most temples having orientations that can be explained either by chance, terrain aspect, protection from wind or winter sunlight, there are some patterns of orientation that cannot be explained by any of these hypotheses. These patterns are only statistically significant for temples of the earlier, Ġgantija phase of construction and they match the rising or setting of neighbouring stars of the southern celestial hemisphere. It is argued that these stellar matches were unlikely to be coincidences in that they probably were important stars for astronavigation (as they still are today) in the central Mediterranean. Finally, we suggest that the temples, in addition to other symbolic or social purposes may have been places of instruction for young seafarers to learn these important navigational stars.

**Keywords** Malta · Temple period · Orientation · Landscape · Skyscape · Statistics

## Introduction

Located about 90 km southeast of Sicily, at the heart of the Mediterranean, the Maltese archipelago is a relatively small region with a land area of just 316 km$^2$ and a population of just above five hundred thousand (WorldBank 2023). The archipelago was colonised by Neolithic people from Sicily around 6000 BC (McLaughlin et al. 2020). During much of the fifth millennium BC, there seems to have been a decline in the human occupation of Malta until a new influx of colonists that kicked-off what is referred to as the Temple Period (3800–2400 BC). This period is named for the contemporary megalithic structures, generally acknowledged as sacred and ceremonial spaces and often referred to as ‘temples’, which Colin Renfrew called ‘the earliest free-standing monuments of stone in the world’ (1973: 161). Several dozens of these prehistoric temples sites are recorded in the archipelago (Evans 1971), although today only nine well preserved sites are left, which are nevertheless majestically conspicuous in the Maltese cultural landscape (Fig. 1).

Their architectural typology – built of local limestone blocks and featuring an entranceway leading to a central court with rooms on either side (Fig. 2) – and sheer sophistication is unique in European prehistory. Together with their scale and number, this has drawn the attention of many archaeologists who have researched their construction, choice of location, iconography, and the wider environment around them (e.g. Evans 1959; Grima 2001; Trump 1966; Malone et al. 2020). Their monumental entranceways, often embedded into concave façades, and leading into axial corridors, led several scholars to wonder whether there was any intention behind their orientation, and whether that may help us understand what these structures were used for (e.g. Agius

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Published online: 03 April 2025

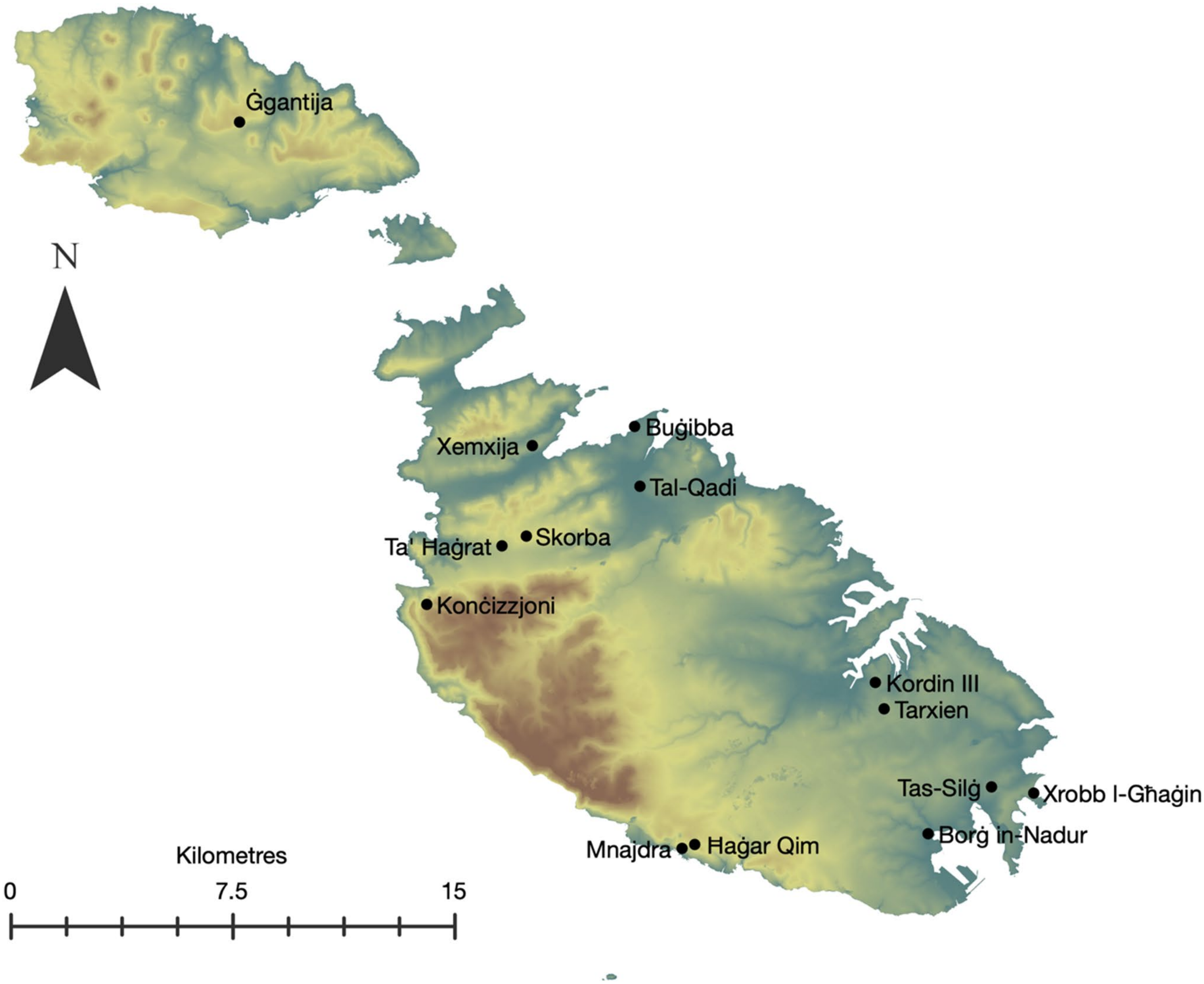


**Fig. 1** The location of the Maltese temples mentioned in this paper

and Ventura 1980; Hoskin 2001; Lomsdalen 2014; Barratt 2022). However, previous attempts have either statistically assessed whether the temples may have been orientated at random, and/or have sought to find celestial explanations for either the identified statistical patterns in orientation, or for the orientation of individual sites. These works have often mentioned, but did not formally test whether other, more pragmatic, explanations such as orientation by following the terrain, for protection against the wind, or for maximising winter light would account for the data. In addition, recent studies (Barratt 2022) have pre-selected a shortlist of celestial objects to compare vis-a-vis the orientation of the temples, rather than allowing the choice of celestial bodies to emerge from the data itself.

We have therefore endeavoured to take a novel approach that deploys the same statistical framework to test the data for temple orientation against a number of hypotheses ranging from randomness, to topographic, climatic and celestial explanations. This is unprecedented not only in the study of Maltese temples but more generally in the study of structural orientations globally and directly answers previous calls for the bridging of landscape and skyscape archaeological approaches (e.g. Ruggles 2011; Silva 2020a). To achieve this, we have taken new measurements of the orientation of the entrances of 32 temples, the largest dataset of Maltese Temple orientations analysed to date. We then adapted Silva's (2020a) probabilistic framework to test this dataset not only against the null hypothesis of random orientation, but also against the other already mentioned potential explanations. Only after excluding such down-to-earth hypotheses did we explore celestial explanations. This last stage was done inductively by searching the region(s) of the horizon highlighted by the statistical method, identifying all reasonably bright celestial objects within said region during the Temple Period, assessing whether they would have been visible, and only then exploring their possible significance

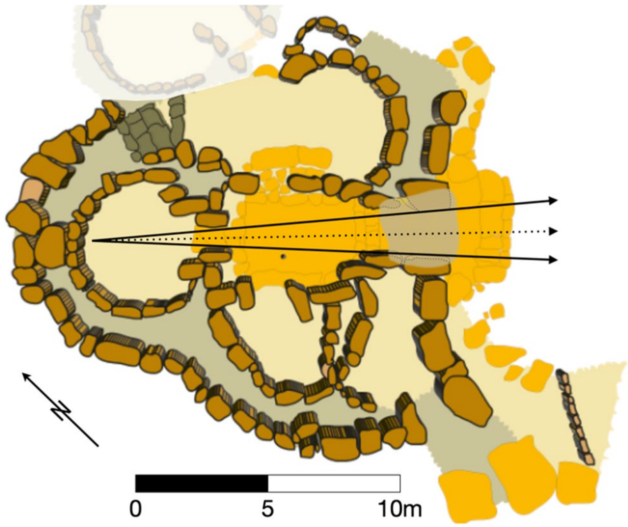


**Fig. 2** Plan of Ta' Ħaġrat temple showing its three apses (beige rooms), paved central court (yellow floored hall) and entrance façade (on the right). Marked are the temple's central axis (dotted arrow) and the orientations measured to define the entrance frame (solid arrows). Plan after Cilia (2004)

within the socio-historic context and lifeworld of the prehistoric Maltese.

## The Maltese temples

The Maltese Temples, built over a thousand-year period, have a remarkable constructional consistency which, together with their strength and stability demonstrate advanced architectural and engineering knowledge (Torpiano 2004: 348). The temples are built from globigerina and/or coralline limestone blocks, extracted from local sources, ranging from 0.5 to 2 tonnes and, exceptionally, much more (Trump 2002: 77–80, Torpiano 2004: 357). They consistently feature a central court with a number of apses or rooms either side, typically two or four in total, with an extra apse, or sometimes merely a niche, in the back; and a concave façade usually surrounded an entranceway (Fig. 2). Whether the temples were roofed or not is still an open question. The corbelling of the walls in some areas do indicate that some space of the building could have been roofed, however how the roofing was executed is unproven (Grima 2005: 47). Retrieved stone models and engravings do suggest some kind of horizontal roofing elements (Torpiano 2004: 355). Trump (2002: 84–85) suggests that timber was applied to support the roof. Some have suggested that although the apses may very well have been roofed, the central court would not have been (Grima 2001: 51). Indeed, the paved nature of these courts, along with artistic representations of sea and fish, is suggestive that they may have been intentionally flooded through natural (e.g. rainwater) or artificial means (Grima 2005: 246–252, 2016: 42).

What these structures were used for is an on-going debate. There are no indications that the temples themselves were used for burials or dwelling. However, there is evidence that at least some of them were built on prior settlements (Grima et al. 2020: 234, McLaughlin et al. 2020: 32). At Skorba, Trump (1966: 10–11) excavated a settlement containing human remains and a shrine which were stratigraphically dated to before the Temple Period. Some of the largest temples, such as Tarxien and Ħaġar Qim, feature spirals and other motifs carved into stone platforms, statues, shelves, altars and oracle holes – all very suggestive of symbolic functions for, at least, some of the rooms. More recently, however, they have begun to be described as 'clubhouses' – 'community buildings that rivalled their neighbours, outcompeting in size, complexity, food, feast and festival' (Barratt et al. 2020: 34, Stoddart 2022). This conception, derived from ethnographic observation of modern-day band clubs, highlights the aggrandising power of non-kinship organisations based around the performance of rituals and associated festivities, commonly known as 'ritual sodalities' (Hayden 2018). However, as they are still commonly referred to as temples both within academia and among the general public, we will here continue to refer to them as either temples or structures.

They are frequently found in clusters, often paired together in locations that offer a high degree of intervisibility (Lomsdalen 2017: 109, 2022: 160). This led some to suggest that their regional patterning reflected a territorial division by a 'chiefdom class' which would have been the driving force behind temple construction (Renfrew 1973: 170–172). The questions of who was behind the construction of these temples, the social rank they held and whether their role was political, religious or otherwise have also been the subject of heated debate. An early argument was that a priestly class must have existed because, in addition to the elaborate temple structures, terracotta figures seemingly portraying priests have been discovered and the fact that the Xemxija rock-cut tombs clearly indicate a privileged type of burial (Evans 1971: 222; 1977:24). Anderson and Stoddart (2007: 43) follow this line of thought, proposing that the sophisticated temples with their hidden rooms could represent private areas for the priests before they appeared in front of a congregation. Others, however, made the case that they may not have necessarily been a priestly class, but that they must have been some kind of ritual specialists (Renfrew 2007:12; Cazzella and Recchia 2015: 106).

Evans (1959: 84–97) suggested that the origin of the oval chambered form of the temples came from earlier kidney-shaped rock-cut tombs in Malta, a custom the first settlers arriving from Sicily could have brought with them, an idea also supported by Trump (2002: 87–88). Although all temples have generally the same lobed form, the number

**Table 1** Maltese prehistoric chronology, recently revised by the *FRAGSUS project* (McLaughlin et al. 2020: 38)

| Period | Phase | Start | End |
|---|---|---|---|
| Neolithic | | 6000 BC | 3800 BC |
| Temple Period | Żebbuġ | 3800 BC | 3600 BC |
| | Mġarr | 3600 BC | 3400 BC |
| | Ġgantija | 3400 BC | 3100 BC |
| | Saflieni | 3100 BC | 2800 BC |
| | Tarxien | 2800 BC | 2400 BC |
| Bronze Age | | 2400 BC | 750 BC |

of apses varies from two to six (Trump 2002: 72, 74). This has been suggested as reflecting an increasing need for more space, perhaps due to an expanding emphasis on the temples and the ideology they represented, or more generally due to an increase in population numbers (Trump 2002: 86–87; Torpiano 2004: 347–349; Anderson and Stoddart 2007). A chronology of the temples has been established based on architectural typologies as well as the material evidence, especially pottery, found in them (Evans 1971). This chronology identifies two key periods of temple construction, with a clear differentiation between those built in the Ġgantija Phase (3400–3100 BC), which feature a broader architectural variety and sophistication, and those built in the Tarxien Phase (2800–2400 BC), where a more standardised and uniform arrangement becomes ubiquitous (Trump 1997: 21, see Table 1). In addition, it is in Tarxien Phase temples that more refined figurines, elaborate artistic and iconographic representations are found (Stoddart and Malone 2008). However, establishing a robust chronology of the temples is difficult as older parts of the buildings could have been destroyed or modified over the years (Grima 2008: 47).

Although these structures undoubtedly played a role in the ideology and cosmology of Neolithic Maltese, they were not the only architectural feature that we know of. These temples had a counterpart in the so-called hypogea used for mass burial, and often also displaying refined artistic depictions and architectural features, such as at the Ħal Saflieni hypogeum (Pace 2004b). This dichotomy between the temples above-ground and the underground hypogea had led some to posit a three-tiered cosmography, with an upper world populated by the celestial bodies and the ancestors, a middle world for the living with the temples acting as pivots, and an underworld for the dead houses in the hypogea (Bonnano and Militello 2008: 59; Stoddart et al. 2009: 376; 2011: 770). Some scholars have also drawn attention to the skilled iconographic depictions in the temples themselves, often featuring sea and land motifs, 'perhaps the two most inevitable components of an islander's cosmology' (Grima 2001: 56; 2005: 253; 2007: 40).

Towards the end of the Temple Period, during its Tarxien phase, Malta experienced a climatic drought which made living from agriculture and arable farming difficult and may have led to a cultural collapse (e.g. Malone and Stoddart 2013) or, at least, a reorganisation of settlement on the island (Grima et al. 2020: 234). Subsequently, the Maltese Bronze Age (2400–750 BC), saw the elaborate temples replaced with simpler and less sophisticated ritual architecture – the dolmens (Evans 1956: 87; Bonanno et al. 1990: 203; Pasztor and Roslund 1997; Malone and Stoddart 2011: 771) – as well as the first appearance of fortifications and evidence for war-like slaughtering (Trump 2002: 239).


**Fig. 3** (**a**) Overhead photograph of the Tarxien horizontal slab (photo by Daniel Cilia, with permission); (**b**) the Southern Cross when rising as seen from Malta around 3250 BC (reconstruction done using *Stellarium* v24.4, Zotti et al. 2021)

## The temples and the heavens

With respect to potential connections between the temples and the skyscape, it was Vance (1842: 232) who first suggested the temples were not roofed in order to better worship the sun, moon and stars. Zammit (1929: 13) mentioned that a slab formation at the Tarxien Temples 'has suggested to some the idea of' the Southern Cross, a constellation in the southern celestial hemisphere that was still observable from Malta during the Temple Period (Fig. 3). Writing in the 1930s, Ugolini (2012: 128) called the engraved Tal-Qadi stone a Neolithic 'lastra astrologica' or astrological plate. Following these early speculations, it was not until the mid to late 1970s that further studies were conducted. The first report of astronomical alignments on summer solstice sunrise and sunset inside the Ħaġar Qim temple (Formosa 1975: 19–21) led to the first survey of the temples by Agius and Ventura (1980, 1981). Agius and Ventura concluded that the temples were not orientated at random, with a statistically significant preference for southeastern and southwestern orientations (see also Foderà Serio et al. 1992). Furthermore, they noted that the Ġgantija Phase temples in their sample had a southeasterly orientation whereas the Tarxien Phase temples had a southwesterly one. Beyond solar and lunar alignments, Agius and Ventura (1981: 16–20) also looked for stellar alignments and concluded that six out of ten temples were oriented towards the two brightest stars of Centaurus during the Temple Period.

Following these ground-breaking studies, archaeoastronomical interest in the Maltese temples exploded (Micallef 1990, 2000; Mayrhofer 1995; Thomson Foster 1999; Vassallo 2000; Cox 2001; Albrecht 2004). Most archaeoastronomical research has mainly been concerned with internal illumination of temples caused by alignments to sunrises and sunsets at the equinoxes as well as summer and winter solstices. A smaller number considered the potential role of alignments to the moon at its extremes (e.g. Agius and Ventura 1980, 1981; Cox 2009; Cox and Lomsdalen 2010; Lomsdalen 2014), and an even smaller number have seriously considered potential stellar alignments. Those that do have typically arrived at similar conclusions to Agius and Ventura's pioneer study although, armed with more robust astronomical calculations, they have tended to favour alignments to the star Gacrux in the Southern Cross (e.g. Cox 2001; Hoskin 2001; Barratt 2022; Lomsdalen 2022). Quantitative approaches, using robust statistical analysis of temple orientations, are equally rare, with the notable exceptions of Agius and Ventura (1980, 1981), Agius et al. (2021), Barratt (2022), and Lomsdalen's (2022) doctoral thesis, which the present paper extends.

Barratt (2022: 1–2) innovated through the use of 3D simulation of temple architecture to assess the accuracy of astronomical alignments. This was done for 23 temples, extruding 3D models from archaeological plans and rectifying them through comparison with published measurements. A small number of celestial targets was then chosen a priori in order to assess the accuracy of alignments through the entirety of the Temple Period. Based on this, he concluded that 'the alignment with Crux [the Southern Cross] is the most significant result found' (Barratt 2022: 13), with nine out of 23 temples displaying such an alignment. Given this, Barratt highlights the potential role of the Southern Cross constellation for navigation and how important that would have been for the prehistoric Maltese in addition to a ritual role (2022: 15–16). However, he checked only a small number of stars, and therefore may have missed other, important stellar alignments, such as the previously mentioned stars of Centaurus.

## Materials & methods

To answer the research question set out above, we will employ and extend the probabilistic framework for the analysis of structural orientations developed by Silva (2020a). This framework involves representing the orientation of individual structures as a probability distribution which can then be aggregated into a *Sum of Probability Densities* (SPD) and used to test for statistical significance against the null hypothesis of random orientation. This test is based on random sampling from a probabilistic model that represents a random distribution of orientations, from which a confidence envelope is constructed and compared to the empirical SPD. The confidence envelope shows the range of possibilities of the null hypothesis and, hence, only wiggles of the empirical SPD that fall outside the envelope are statistically significant. Such regions of significance, where the empirical SPD is significantly above or below the confidence envelope of the null model, are highlighted by this method and should form the basis for further interpretation. Global p-values provide a measure of whether the entire dataset constitutes evidence against the null hypothesis of random orientation. On the other hand, local p-values measure whether the sub-set of the data with a given orientation (the 'local' region) constitute evidence against the null hypothesis. The interpretation of the results should primarily be based on global significance (the global p-value) and only secondarily on local significance (the local p-value). A p-value lower than 0.05 is deemed significant (see discussion around this in Silva 2020a: 2).

A key advantage of this analytical framework is that it can be extended to accommodate a variety of models for the null hypothesis (*null models* henceforth) which, as Silva highlighted (2020a: 11), can encompass both terrestrial and celestial explanations. We realise this framework's potential to bridge the gap between landscape and skyscape archaeology by testing the statistical significance of the orientation of the Maltese temples against a number of topographical, geographical and astronomical hypotheses, the details of which are below. This is achieved by adapting Silva's methodology to work with any inputted null model. This must necessarily take the form of a probability density function and it can be singular, in which case it will be applied to all sites, or it can be provided in the form of a series of probability density functions, each of which applies to each site. This last extra level of complexity is a necessity which will become apparent when we discuss some of the topographical hypotheses we are testing.

The analysis was conducted in the R statistical programming language and used *skyscapeR* (Silva 2021) as its backbone, as it implements the probabilistic framework and significance test that underlie the methodological development just described. Source code for the analyses will be made available on the authors' GitHub page upon publication.

## Orientation data

Due to their symmetric architecture and the use of flat-faced megaliths, measuring the orientation of the central axis of the Maltese temples is a relatively simple exercise that has been done by a number of people resulting in comparable measurements (Agius and Ventura 1981; Cox 2001; Hoskin 2001; Ventura 2004; Lomsdalen 2022). This typically involves locating a point along its axis and measuring the orientation from that point towards the midpoint of the entrance. What is often ignored or underestimated is the level of uncertainty in those measurements – a problem that is not unique to the study of Maltese prehistory (Silva 2020b). The largest uncertainties in these measurements originate not from the instruments used but from the choices made by the researcher, for example of where to take the measurement from, as well as from the very materiality of the structure itself (Silva 2020b: 60–66).

In his study of Iberian passage graves Silva has used the diagonals provided by the passages as the measure of uncertainty, as they provide the minimum and maximum azimuths possible (Silva 2012). However, those structures are smaller, contain only one chamber at the end of the passage, are built out of rougher megaliths and show little interest in straight lines. In the case of the Maltese temples, the main axis is more clearly defined and is differentiated from the rest of the structure, whose apses are separated from the axis by entranceways. We have therefore chosen to use a more conservative estimate of uncertainty by taking into account the width of the entrance as seen from the back of the temple (see Cox 2001 for a similar consideration although differently implemented). Although this does not take fully into account the various viewpoints and perspectives offered by the entrance when one moves inside these structures it is still a considerable step forward from previous studies. As an example, Agius and Ventura (1980) acknowledged only 2° error in their measurements of the central axis. By contrast, we have found that the width of the temple entrances, when viewed from the back of the temple, results in viewing windows of no less than 3° and with a maximum of about 16°, averaging at about 9° (see Table 2). We have therefore taken two horizontal measurements at each site (see Fig. 2). Our results are presented in Table 2 and compared with those of previous studies in supplementary table S1.

Azimuthal and altitudinal measurements were taken in situ with a SOKKIA SET5 Total Station, whereas a Garmin eTrex 30 GPS handheld was used for georeferences. Ruggles' (1999:164–171) sun-sight method which calibrates the total station's measurements by taking an extra reading of the azimuth of the sun was used. The height of the total station was set at 1.60 m so that our measurements, especially the altitude, approximated the view possible to the average prehistoric Maltese (Stoddart et al. 2009: 325). To ensure that no large or systematic errors were made, a Suunto survey-grade compass and clinometer tandem was also used to take the same measurements as the total station. In a handful of instances – Tal-Qadi, Konċizzjoni, Tarxien East, Xrobb I-Għaġin, and Xemxija – the ruined state of the site and the presence of modern vegetation made in situ measurement difficult. In this case, accurate archaeological plans were used to assist and complement the field survey.

**Table 2** Measurements of the entrance frame (min and max azimuths) of all 32 structures, with associated chronological phase

| Structure | Phase | Entrance Azimuth ° | |
|---|---|---|---|
| | | Min | Max |
| Mnajdra South | Ġgantija | 90.94 | 99.14 |
| Mnajdra Central | Tarxien | 135.24 | 140.45 |
| Mnajdra East | Ġgantija | 197.91 | 211.77 |
| Ħaġar Qim East | Ġgantija | 123.93 | 134.44 |
| Ħaġar Qim West | Ġgantija | 301.62 | 314.61 |
| Ħaġar Qim Room 10 | Ġgantija | 294.20 | 301.20 |
| Ħaġar Qim Room 11 | Ġgantija | 349.66 | 5.32 |
| Ħaġar Qim Room 12 | Ġgantija | 249.69 | 259.64 |
| Ħaġar Qim Room 13 | Ġgantija | 201.60 | 214.96 |
| Ħaġar Qim North | Tarxien | 183.44 | 189.87 |
| Borġ in-Nadur West | Tarxien | 112.09 | 126.46 |
| Borġ in-Nadur East | Tarxien | 94.83 | 107.32 |
| Tas-Silġ East | Tarxien | 99.90 | 109.74 |
| Tas-Silġ West | Tarxien | 277.52 | 293.02 |
| Xrobb I-Għaġin | Ġgantija | 124.00 | 132.00 |
| Tarxien South | Tarxien | 196.50 | 202.70 |
| Tarxien Central | Tarxien | 226.20 | 233.20 |
| Tarxien Room 10 | Tarxien | 139.70 | 142.70 |
| Tarxien East | Uncertain | 193.88 | 206.41 |
| Tarxien Far East | Ġgantija | 165.56 | 172.51 |
| Kordin III West | Ġgantija | 146.56 | 151.25 |
| Kordin III East | Ġgantija | 194.68 | 203.96 |
| Ta' Ħaġrat West | Ġgantija | 127.09 | 135.15 |
| Ta' Ħaġrat East | Ġgantija | 168.50 | 182.70 |
| Skorba West | Ġgantija | 128.55 | 138.07 |
| Skorba East | Tarxien | 165.59 | 173.62 |
| Konċizzjoni | Tarxien | 265.20 | 270.70 |
| Buġibba | Tarxien | 182.63 | 190.01 |
| Tal-Qadi | Tarxien | 64.53 | 74.82 |
| Xemxija | Uncertain | 134.20 | 146.20 |
| Ġgantija South | Ġgantija | 127.57 | 131.36 |
| Ġgantija North | Ġgantija | 128.89 | 135.35 |

## Orientation model

The first stage of the analytical framework involves choosing a probability distribution to model the orientation measurements (Silva 2020a: 11). We have elected to use a normal distribution constructed from the measurements of the temple entrances as follows. The midpoint of the entrance frame is taken as the mean of the normal distribution, and its standard deviation is a quarter of the entrance width. This model ensures that we have 95% confidence that the "true" orientation – meaning the orientation as conceived by the temple builders – is somewhere within the range given by the entrance frame. The remaining 5% is left off to avoid any hubris regarding the accuracy and precision of the measurements themselves. The model also assumes that the "true" orientation is more likely to be closer to the centre of the entrance frame, rather than to its sides. This seems like a plausible assumption on our part, considering the overwhelming evidence for symmetry and axiality within the sophistication of architectural and engineering techniques (Pace 2004a: 30; Torpiano 2004: 360–364). In addition, both figurines and symbolic representations often feature symmetry (Bonanno 2004; Tilley 2007). Nevertheless, we have rerun our analyses with a uniform model that makes no such assumption (Silva 2020a: 2–3) and obtained results comparable to those presented here, with only minute and inconsequential variations.

## Landscape hypotheses

Our exploratory analysis begins by looking at the possibilities that involve the least number of assumptions. We therefore begin with landscape explanations for orientation. There is a vast array of such possible explanations that could be tested with our methodology, but we have selected four based on prior studies and other mentions in the wider literature. They are: (a) orientation at random; (b) orientation by aspect; (c) orientation for protection against the wind; and (d) orientation to maximise sunlight in winter months.

The first test is the one where the orientation measurements are compared to what would be expected under the null hypothesis of random orientation (Silva 2020a). The model for the null hypothesis is therefore a uniform distribution in azimuth, from which 10,000 samples with the same size as the empirical dataset were taken at random, aggregated and used to obtain the confidence envelope of the null. The p-value resulting from this test is therefore a measure of whether the orientations of the Maltese temples can be the result of random chance.

Several scholars have highlighted the need to take the topography of the landscape into account when considering temple orientations (Turnbull 2002: 132; Grima 2005: 191). Grima's seminal studies on the landscape context of the Maltese temples (2002, 2004, 2005) provide a first port of call for this. Although his focus was largely the location of the temples rather than their orientation, Grima (2004: 337–340; 2005: 191–192) identified no preference for temples to be built on higher or lower grounds, nor on steeper or shallower slopes. He did, however, note that southern facing slopes were preferred by the temple builders, with a secondary preference for western facing ones (Grima 2004: 340), although "aspect alone does not explain the site distribution pattern" (Grima 2004: 341).

To test whether the orientation of the temples could be explained by the aspect of the surrounding landscape, we constructed a null model as follows. A DTM with 5 m resolution LiDAR data, made available thanks to the Planning Authority, was used to calculate the aspect using the *terrain* function of R package *raster* version 3.6–14. Rather than simply taking the raster cell corresponding to the GPS coordinates, a buffer was implemented because the aspect calculated in such a way can change quite considerably from one cell to the next. It is also impossible to predict where exactly the aspect would be measured and/or marked in situ if it were to be the defining factor in laying out the axis of a temple. The aspect values for each cell within a 30 m radius around the GPS coordinates of each structure were then queried and saved. The value of 30 m was used as it is sufficient to encompass the area of even the largest of Maltese temple complexes, such as Tarxien, Ħaġar Qim or Mnajdra. Hence, to mimic the effect of taking an azimuth based on the aspect in situ, from the 30 m buffered values we save the mean and standard deviation and use them to construct an individual null model for the aspect of each site.

Grima concluded that "the most plausible explanation for the preference for southern slopes is a preference for the conditions that these slopes afforded, such as better exposure to sunlight, or shelter from northerly winds" (2005:191). We therefore decided to also test these two hypotheses. Starting with the latter, the wind, weather and climate in Malta is conditioned by southerly continental tropical dry, warm air masses from Africa in the summer and northern dry and cold continental polar air masses lowering the temperature and increasing rainfall in the autumn and winter (Schembri 2019: 11). Dominant winds arrive from the northwest and the west (Marriner et al. 2012:2; Zammit Pace et al. 2019: 213–214) and the most extreme wave and weather events are arriving from northeast direction (Mottershead et al. 2019: 273, 283–285). Whether protection from the harsh northern wind direction was responsible for orientating the temple entrances towards southern orientations is a possibility that should not be disregarded. Statistical analyses of the climatic trends of Malta from 1951 to 2010 reveal the most common wind direction to be the North-westerly on an average of 20.7% of the days in the year (Galdies 2011: 19–20). This data can be used as the basis for a null model to test whether the temples were orientated to provide protection from the wind. The null model was constructed by taking the wind direction distribution data from Galdies (2011) and flipping it by 180°. This assumes that the best protection from the wind is offered by orientating the temple axis exactly against the wind. This may not be completely accurate, especially considering that the airmass movements may have been different in prehistory. However, as will be clear in the results, this choice actually provides the toughest possible null model to test the empirical data against.

Finally, we also test for exposure to sunlight which is only problematic in the colder winter half of the year. Although technically this can be perceived to be a skyscape explanation we have decided to include it here since, as we've seen, it is often mentioned as an explanation for the temple builders' preference for southern facing slopes and because a concern for sunlight doesn't necessarily involve an alignment with the sun at a specific moment in time, but rather a looser orientation towards this celestial object. Our null hypothesis here is therefore that the orientations were chosen so that the temple entrances were facing the sun, at a random time and date, during the winter half of the year. We constructed the null model by obtaining azimuths for the sun for every minute of every day, between sunrise and sunset, between the autumn and spring equinoxes in the year 3000 BC (little variation in solar position happened during the period 3800−2400 BC). This was done using the R package *swephR* which fast computation of the position of celestial objects (Reijs and Stubner 2020). It replicates NASA Jet Propulsion Laboratory's data to within 0.001 arcsecond accuracy and includes in its calculation all known astronomical and atmospheric phenomena, including precession, nutation, parallax and refraction.

The significance testing algorithm then takes these null models and, for the corresponding site, picks a random azimuth from them. To this azimuth is attributed the same measurement uncertainty as that of the structure orientation, to mirror the fact that the structure may encode the right azimuth while still allowing for a margin of error given by the existing entrance frame. This is then repeated several thousand times and used to get a confidence envelope and p-value as per the Silva (2020) method.

Other tests, based on alternative explanations for structural orientations, in Malta and elsewhere, were also considered but rejected on independent grounds. Grima already considered and rejected a visual relationship to the sea (2005: 136), as well as a link to Sicily or Pantelleria (2005: 191). Alignments to topographic features such as peaks or notches on the horizon, which feature in prehistoric monuments elsewhere (e.g. Silva 2015; Lozano et al. 2014) also do not play a role here (cf. Lomsdalen 2022). The directions of migratory bird flyways were also considered by us, especially due to Malta's central Mediterranean location being so close to the important migratory flyways. However, radar observations indicate that Malta is not a stepping-stone on the seasonal migration of birds between Europe and Africa (Casement 1966: 485). Although this may have been different in the past, without any flyway direction data this is simply impossible to test using an analytical framework.

Finally, it is important to highlight that p-values obtained from separate significance tests are not comparable and, therefore, cannot be used for model selection purposes (Wasserstein and Lazar 2016). Therefore, the p-values will be interpreted on a case-by-case basis as quantifying the evidence for each null model, but they will not be used to choose which null model(s) best fits the data.

## Skyscape hypotheses

To test for statistical significance of celestial explanations requires transforming the measured orientations into celestial coordinates that represent the locations in the celestial sphere that the temple entrances are facing (Silva 2020a: 3–5). This requires horizon profiles from each site, which can be used in the coordinate-transformation process. Because of modern buildings, these were not always possible to obtain in the field. Therefore, the same 5 m DTM mentioned above was used to digitally reconstruct the horizon. The reconstruction was done using *Horizon* v0.13c, which is a GIS tool designed to calculate accurate horizon profiles from DEM/DTM mapping data (Smith 2018). Visual inspection and comparison in situ and using panoramic photographs resulted in qualitatively accurate horizon profiles. However, some differences between calculated horizon altitudes in this way and field measurements have been observed before (Reijs 2015) and it is a known fact that DTMs may contain spatially variable vertical measurement errors (Mukul et al. 2015) which can negatively and significantly affect such digital reconstructions. As such, where possible, field measurements with a total station were taken and compared with those obtained in Horizon (see supplementary table S2). This comparison resulted in a mean error of 0.38° ± 0.07°, although the distribution of errors is non-normal. We have therefore decided to take a more conservative approach and, instead of taking the mean, we chose the 95th percentile of these errors, rounded to a single decimal place (1.7°) and used it as the uncertainty in the altitude of the digitally reconstructed horizons.

These horizon profiles were then used to coordinate-transform the orientation measurements from azimuth distributions into *declination* distributions using the method developed in Silva (2020). Declination is a celestial coordinate which is measured along a great circle line that connects the north and south poles of the celestial sphere, making it analogous to latitude on the Earth's surface (Kelly and Milone 2005: 16–20). This coordinate is sufficient to describe where a given celestial object will rise or set on the horizon and what trajectory on the celestial sphere it will follow. It therefore can be used to identify potential targets of alignment. The obtained declination distributions are then aggregated and undergo the same significance testing methodology described above.

The only null model employed here is the one used in Silva (2020), i.e. that of random orientation. Therefore, we are not explicitly testing the data against particular celestial hypotheses (as done above for the three landscape hypotheses considered), but merely testing the null hypothesis of random orientation (i.e. the equivalent of the first landscape test). This is necessary in order to remain open to a broad range of celestial objects and events that may have been targeted. As such, ranges of declination that provide statistically significant deviations from the null model will then be the object of further study, to identify celestial objects matching those declination values and then assess, firstly, whether or not they may have been visible, and secondly, whether they may have had any socio-historic significance. Finally, the Stellarium v24.4 open-source planetarium software (Zotti et al. 2021) was used for visualisations of the sky and the identification of celestial objects that match statistically significant orientations.

### Chronological divisions

Grouping all of these temples together is not necessarily the most informative approach since this can blur regional and/or chronological signals (Silva 2014). Trump (1997: 21) makes a distinction in temple architecture between the Ġgantija and Tarxien phases. A great variety and originality in temple architecture is seen in the Ġgantija phase, whereas the Tarxien phase is characterised by endless repetition of a standard form. The latter phase also features fresh iconographic activity with figures ranging from over two metres tall to mere millimetres (Trump 1972: 21). This led Trump to suggest an ideological shift to have occurred between the two phases (1972: 21). Such changes could also be reflected in the orientation of the temples, as already suggested by some scholars (Agius and Ventura 1980: 8, 1981: 14; Cox 2001: 28;). For this reason, we have decided to re-run the above tests for sub-samples of Maltese temples belonging to different chronological phases.

However, dating the Maltese temples is very challenging as they are sometimes built on older sites and can be in continuous use through various phases (Evans 1971: 34). Grima (2008:35) suggested that the temples appear not to follow a single master plan nor were they conceived at a single moment, but rather extended, modified and altered over a longer period of time. We have therefore aimed to capture the chronological phase that corresponds to the construction of the central axis and entrance of the temple, or room within a complex, in question (Table 2). This information, including references for the phasing, is detailed in the supplementary table S3. Tarxien East and Xemxija, due to their uncertain chronology, are excluded from these analyses.

### Methodological limitations

We consider this analytical framework to be quite robust for answering the research question introduced above. Its limitations relate to what it is not attempting to answer. Firstly, as already mentioned, the measurements do not account for the full range of possible orientations afforded by the architecture of the Maltese temples, what Silva (2020b: 72) called the 'materiality uncertainty'. For example, offset and cross-jamb orientations that have in the past been considered in solar illumination studies (Vassallo 2000; Lomsdalen 2014; Ventura and Agius 2017) are not taken into account. This was done by design as we wanted to explore the main axial orientation of the temples first, leaving alternative suggestions requiring more assumptions for future research. Secondly, we note that this methodology is concerned with statistical significance and not intentionality (Silva 2020a: 11–12). A statistically significant pattern in orientation may not be the result of intentional orientation but of secondary concerns – for example, orientating a structure to follow the aspect of the terrain can "feel" natural without it being the result of a conscious intentional choice. Furthermore, not all intentional acts will result in statistical significance. Therefore, intentionality cannot be based solely on the coincidence of structural orientation and celestial object, nor can it be based solely on statistical verification – it can only be argued with recourse to the archaeological and socio-historical context and, therefore, this forms an important component of the discussion below.

## Results and discussion

### Landscape hypotheses

The results of the significance tests with respect to the four landscape elements described in the preceding section are shown in Fig. 4. Looking at the global p-values, all of which are below accepted thresholds (Silva 2020a: 2), the tests indicate that the orientations of the Maltese temples cannot be fully explained by any of the four landscape elements.

The first observation from the random orientation test (Fig. 4a) is that northern orientations – from 315° (NNW) to just after 45° (NNE) – are largely absent from the dataset with the exception of a single structure (Ħaġar Qim Room 11). However, this absence is not statistically significant

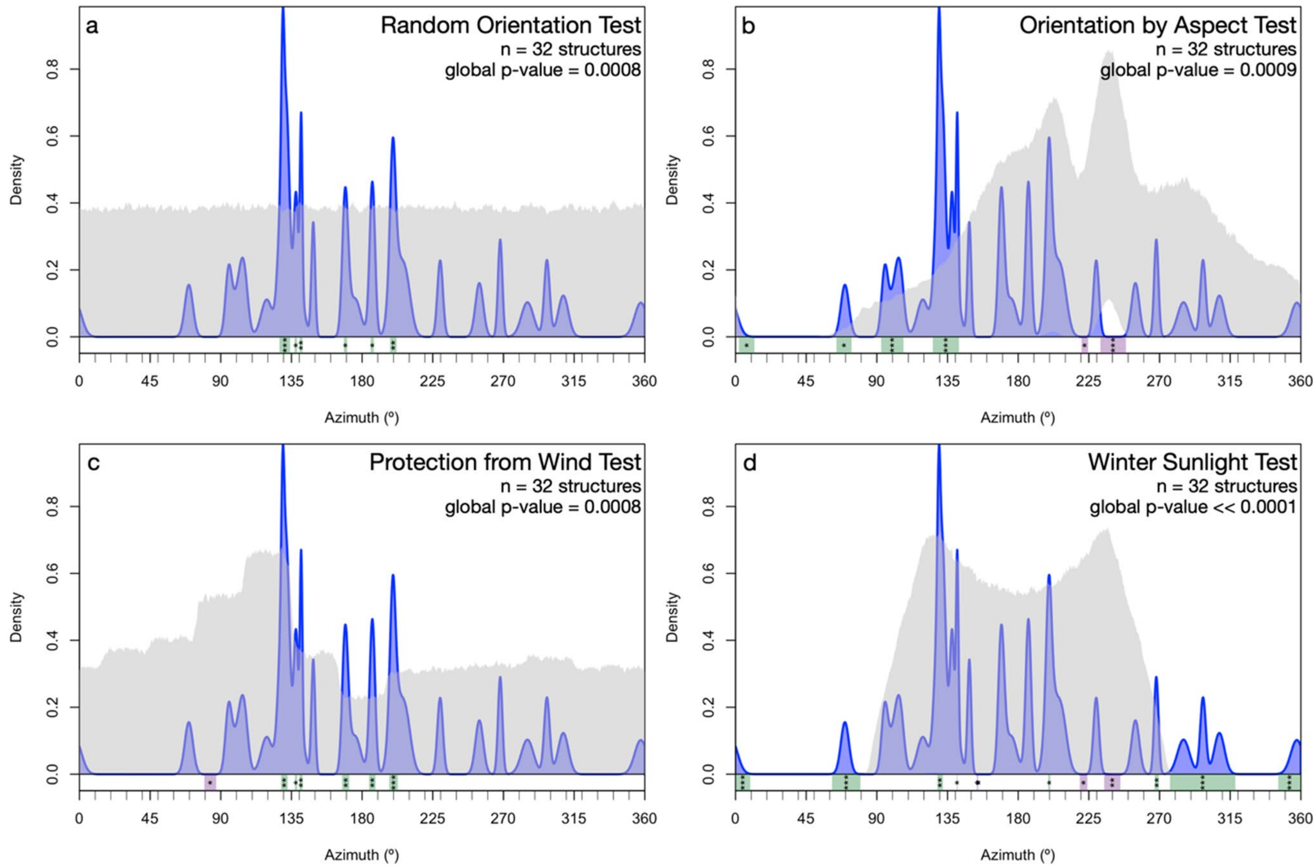


**Fig. 4** Significance test results for all 32 structures against the null hypotheses of: (**a**) random orientation, (**b**) orientation to terrain aspect, (**c**) orientation for protection against the wind, and (**d**) orientation to maximise exposure to sunlight. Shown is the SPD (blue-shaded curve), the confidence envelope of the null hypothesis (grey-shaded area) and the regions of local significance (green and purple highlighted regions at bottom), with stars denoting their level of local significance

since this region was not highlighted as a region of significance. More importantly, there are a number of density peaks, especially those around azimuths 130°, 140° and 200°, that are higher than the confidence envelope of the null hypothesis and are therefore regions of significant positive deviation. These orientations are more frequent in the dataset than would be expected if the temples were orientated at random. These same peaks are also statistically significant in the other tests, especially those around 130° and 200°.

The aspect test (Fig. 4b) equally reveals the null hypothesis to be insufficient to account for all of the orientations. In particular the peak around 130°, as well as the eastern orientations, do not conform to the expectation of this null model. Therefore, although the prehistoric Maltese may have intentionally selected locations with a southern facing slope to build their temples, they seem to have had different motivations behind the orientation of a significant number of their temple entrances.

The third test conducted was against the null hypothesis of protection against the wind (Fig. 4c). Once more, this is insufficient to explain all of the orientations in the dataset since the peaks around 130° and 200°, as well as the southernmost orientations, do not conform to the null hypothesis. One must bear in mind here that protection from the wind was defined as a 180° shift from the wind direction, which may not be realistic. However, as Fig. 4c shows, a shift of any other value would have resulted in even more statistical significance since the highest region of the null model would no longer coincide with the tallest peak in the empirical SPD.

Finally, the global p-value of the fourth test (Fig. 4d) indicates that the orientations cannot be explained by an interest in orienting the temples so that they face the sun during wintertime in order to maximise sunlight. Several structures have orientations that do not face the sun at any point in the winter and even for the ones that do face the sun in winter there are some peaks that are too high to be explained by this null hypothesis.

Looking more broadly at all four tests, it is apparent that, although several of the temples fall within the confidence envelopes of one or several of the null models, there are

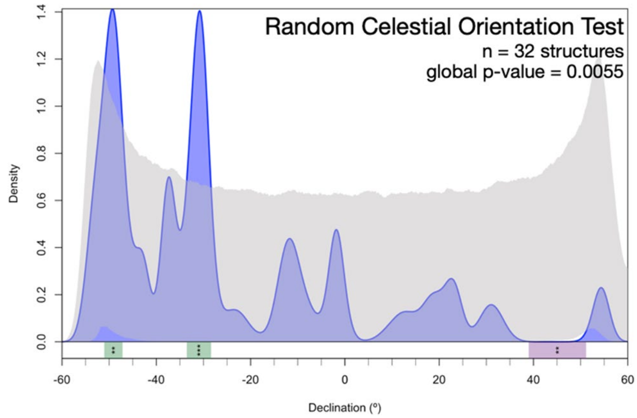


**Fig. 5** Results of the significance test for the orientation of all 32 structures, showing the SPD (blue-shaded curve), the confidence envelope of the null hypothesis of random orientation (grey-shaded band) and the regions of local significance (green and purple highlighted regions at bottom) with stars denoting their level of local significance

**Table 3** Regions of local significance identified by the significance test of Fig. 6, including whether the significant deviation was above (+) or below (-) the null hypothesis confidence envelope, the declination range of the region and associated local p-value

| Deviation | Declination | | Local | Structures |
|---|---|---|---|---|
| | Min | Max | *p*-value | |
| + | -51.0° | -47.2° | 0.0017 (**) | Mnajdra East, Ħaġar Qim Room 13, Tarxien South, Tarxien East, Kordin III East, Ta' Ħaġrat East, Skorba East |
| + | -33.5° | -28.4° | << 0.0001 (***) | Ħaġar Qim East, Xrobb I-Għaġin, Tarxien Central, Ta' Ħaġrat West, Skorba West, Ġgantija South, Ġgantija North |
| - | 39.0° | 51.2° | 0.0026 (**) | none |

peaks of high density that cannot be explained by any of these null hypotheses. In particular, the peak around 130° is identified as being significant by all four tests, with a second peak around 200° being significant in three out of the four tests.

**Table 4** Regions of local significance identified, including the declination range of the region and the associated local p-value

| Phase | Declination | | Local | Structures |
|---|---|---|---|---|
| | Min | Max | *p*-value | |
| Ġgantija (***) | -49.4° | -47.5° | 0.0189 (*) | Mnajdra East, Ħaġar Qim Room 13, Kordin III East, Ta' Ħaġrat East |
| | -33.7° | -28.1° | << 0.0001 (***) | Ħaġar Qim East, Xrobb I-Għaġin, Ta' Ħaġrat West, Skorba West, Ġgantija South, Ġgantija North |
| Tarxien (ns) | -38.4° | -36.4° | 0.0107 (*) | Mnajdra Central, Tarxien Room 10 |

## Skyscape hypotheses

The orientation data were then transformed into celestial coordinates and underwent another significance test against randomness. The results are shown in Fig. 5, and they once more exhibit statistical significance. Due to the effects of coordinate-transformation discussed by Silva (2020: 3–4) this SPD is smoother and features fewer peaks. Only three regions are identified as being significant (Table 3), the declinations between 39° and 51°, which are absent from the dataset, and two peaks that jut above the confidence envelope. These correspond to the two peaks around 130° and 200° of azimuth that were also highlighted as significant in the landscape tests above.

One can therefore conclude that the orientations of the Maltese temples are statistically significant when looked at in declination and cannot be explained solely by random chance. The two regions of significant positive deviation are the places to start looking for celestial targets, which are considered below.

## Chronological variation

As a last analytical result, we have split the dataset into the chronological phases of each structure to check whether different phases offered different patterns in orientation. The results shown in Fig. 6; Table 4 are for the skyscape significance test as we found that the declination SPD offers a

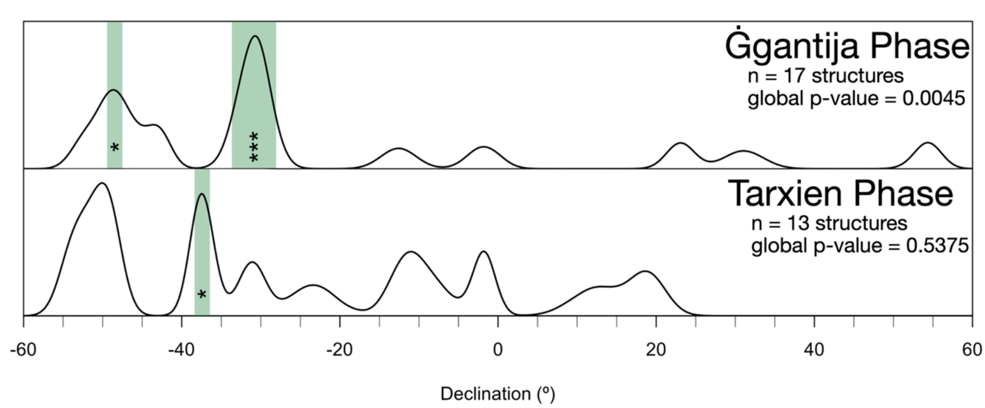


**Fig. 6** Simplified view of the results of the significance test for the orientation of structures of known chronological phase. Shown are the SPDs (black solid curves) and the regions of significant positive deviation from the null model (green vertical bands) with stars denoting their level of local significance

better summary of the dataset. Equivalent figures for all the landscape tests offer similar results and interpretations, and can be found in the supplementary information.

When aggregated according to chronological phasing, a narrative emerges. Firstly, only structures built during the Ġgantija phase exhibit a significant global p-value, meaning that only this sub-set of Maltese temples presents sufficient evidence against the null hypothesis of orientation by chance (see also supplementary information for similar results on the landscape tests). During this phase, declinations between −33.7° and −28.1° are statistically significant (Table 4), with a second, less significant region around −48°. Tarxien phase orientations present a high global p-value indicating no statistically significant evidence against the null hypothesis. This SPD features a single peak of local significance between −38.4° and −36.4°, a range of orientations that is completely absent from the Ġgantija subset. On the other hand, the declination range that was deemed most significant during the Ġgantija phase is, in the Tarxien phase, underplayed and only represented by a single structure (Tarxien Central, which is discussed further below). Finally, two structures that could not be allocated a chronological phase present no significant evidence against the null hypothesis, not unsurprisingly considering the small sample size. Their orientations, however, match the secondary peak of the Ġgantija phase (which also appears in the Tarxien SPD, albeit with no significance) and the Tarxien phase peak. Collectively, these observations will form the basis for the socio-historic contextualisation and interpretation that follows.

Therefore, the chronological split of the dataset reveals very different stories for the Ġgantija and Tarxien phases. Despite presenting a similar range of orientations, only structures from the Ġgantija phase present global statistical significance. This is not to say that all Ġgantija phase structures have the same orientation – which is not the case – but rather that it is only in this phase that a clear statistically significant pattern is visible in the available data. This is the cluster of structures orientated towards declination of around −31°, an orientation that, with the single exception of Tarxien Central, is absent from the range of orientations of Tarxien phase structures.

This noteworthy orientational difference opens up some interesting hypotheses worthy of further investigation. First, the already mentioned variety in the Ġgantija phase architecture is contrasted by the similarity in orientation (at least of some structures from this period). On the other hand, the similarity of architecture of the Tarxien phase is contrasted by a lack of orientation pattern. A key follow-up question is why are the Ġgantija orientation patterns absent from Tarxien phase structures in general? It could be that the Tarxien phase represented a break with previous tradition as also suggested by the change in burial practices (e.g. Pace 2022), and that said orientation was considered a core element of that past tradition to be avoided. It is also possible that Ġgantija phase structures continued to be used through the Tarxien period and that, therefore, new structures with the same orientation and potentially alignment, were not necessary (Lomsdalen 2014; Evans 1971: 29, Trump 2002, p. 137, 154, 156, Trump 1966). Another possibility is that the targets of these alignments, celestial or otherwise, were either no longer visible or no longer socially accepted, valued or meaningful. Either way, these results contribute to the on-going debate about this transition.

Secondly, our analysis makes it patently clear that Tarxien Central has an orientation that could be said to be typical of the Ġgantija phase, despite it being attributed a Tarxien phase construction. It could be that this attribution needs to be reconsidered, that Tarxien Central was built over a prior (perhaps smaller) structure, or that it was "looking backwards" in the sense of holding on to beliefs and meaning characteristic of the previous phase.

## Alignment targets

The results are clear in that there are some statistically significant patterns of orientation that cannot be explained by random chance, terrain aspect, protection from the wind or as an attempt to maximise winter sunlight. In addition, as mentioned above, other explanations including orientation to topographic features are equally insufficient. What then could the prehistoric Maltese have been targeting?

Figure 7 below compares the results of the significance test in declination with the solar and lunar ranges (yellow and grey horizontal bands). Throughout their daily, monthly and yearly cycles, the sun and moon only ever pass through a certain portion of the celestial sphere, corresponding to the declination ranges shown. Although several temples have orientations that fall within these ranges, none of them are statistically significant. The southernmost maximum lunar extreme (the one with negative declination) falls within one of the regions of significance, but the two significant peaks are outside of both the solar and lunar ranges. This suggests that, if indeed celestial objects were being targeted, one will have to consider the stars (see Fig. S3 for the comparison of lunar and stellar targets).

Stars are often dismissed, or outright ignored, in archaeoastronomy due to their sheer number and the adage that "there's so many of them that any orientation will match a few stars". However, the repetition of this adage betrays both an insensibility to cultural astronomy and a lack of phenomenal experience of the night-sky. The former because the stars are an intricate and ubiquitous part of the skyscapes of all societies, past or present (e.g. Urton 1981; Campion

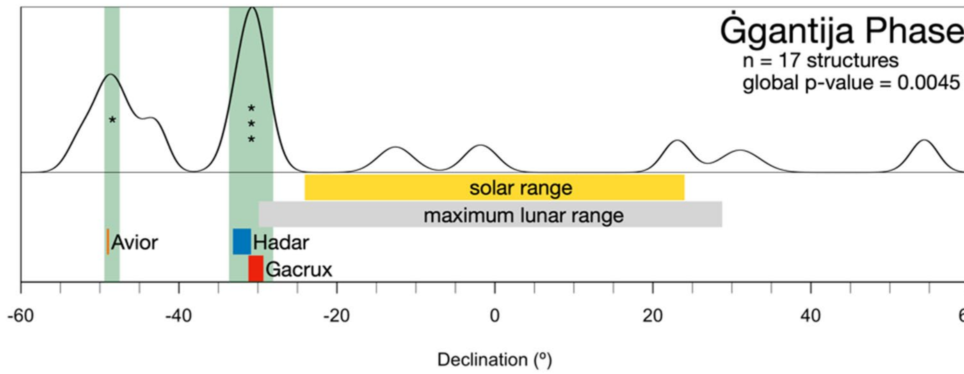


**Fig. 7** Comparison of the regions of significance for Ġgantija phase structures (green bands) with range of declination of the sun (yellow band), moon (grey band) as well as the three stars identified as most likely targets

**Table 5** List of bright stars matching the identified regions of significance for structures of the Ġgantija phase, including the stars' name, bayer designation, apparent magnitude, and declination at the start and end of the Ġgantija phase. Declinations shown in red are outside of the corresponding region of significance. The stars highlighted in bold are the most likely targets, as discussed in the text

| Region of Significance | Name | Bayer | App. Mag. | Declination | |
|---|---|---|---|---|---|
| | | | | 3400 BC | 3100 BC |
| -49.4° to -47.5° (*) | Avior | ε Car | 1.86 | -49.0° | -49.2° |
| | Peacock | α Pav | 1.92 | -47.6° | -49.2° |
| -33.7° to -28.1° (***) | Rigil Kentaurus | α Cen | -0.1 | -33.3° | -34.8° |
| | **Hadar** | **β Cen** | **0.58** | **-31.8°** | **-33.2°** |
| | Mimosa | β Cru | 1.25 | -32.4° | -33.6° |
| | **Gacrux** | **γ Cru** | **1.64** | **-30.1°** | **-31.2°** |
| | Wezen | δ CMa | 1.84 | -31.5° | -30.6° |
| | Mirzam | β CMa | 1.97 | -29.6° | -28.3° |
| | Suhail | γ Vel | 2.21 | -32.2° | -32.1° |
| | Aludra | ε CMa | 2.45 | -32.1° | -31.3° |

2012; Hamacher 2022) and their relevance should therefore not be immediately discounted. Furthermore, the notion that any orientation can match a rising or setting star is nonsensical when one considers the fact that only the brightest stars can be seen so close to the horizon. When this fact is taken into account, and the overwhelming ethnographic and historical evidence is weighed in, then the odds turn in favour of stellar alignments – although this is not to say that one should proceed without care.

We have used the *findTargets* function of *skyscapeR* v1.1 (Silva 2021) to identify all stars brighter than magnitude 2.5 that in the period 3400−2400 BC would have appeared within the regions of significance highlighted by the above analysis (Table 5). This magnitude (a measure of the star's brightness) was chosen as a cut-off as it corresponds to stars that are visible even in the light-polluted skies of modern London and, therefore, would definitely have been bright enough in prehistoric skies. Interestingly, several of the identified stars are included in the list of stars possibly observed and tallied at the tally slabs of Mnajdra East (Ventura et al. 1993; Agius et al. 2021), one of the Ġgantija phase structures that aligns with Avior and/or Peacock. Of all the stars identified as potential targets, we highlight Avior, Hadar and Gacrux due to the fact that they are the brightest stars that are within the regions of significance throughout the entire phase. Others, like Peacock, Rigil Kentaurus, Mimosa and Wezen are still possible, but they are fainter, the alignments occur only towards the beginning or end of the respective phase, or they appear only at the margins of the region of significance.

Our analysis is not the first to highlight Gacrux and the stars of the constellation of Centaurus (Rigil Kentaurus and Hadar) as potential targets of alignment for the Maltese temples. As mentioned above, some significant past studies had already done so (e.g. Agius and Ventura 1980, 1981; Hoskin 2001; Cox 2001; Barratt 2022; Lomsdalen 2022). In particular, Lomsdalen (2022) had also noted the alignment to Avior, but not Hadar, whereas Agius and Ventura (1980, 1981) observed the alignment to Hadar but (wrongly) rejected it due to extinction.

## Stellar visibility

A follow-up question that needs to be answered is whether these stars were visible so close to the horizon that their alignments to the Maltese temples could have been perceived with the naked eye. The earth's atmosphere acts to extinguish starlight, and this effect is compounded the lower the stars are in the sky, i.e. the closer they are to the horizon. This effect was accurately modelled by Schaefer (1986), whose equations can be used to assess the visibility of these stars as they were framed by the entrances of the Maltese temples. Table 6 shows the result of this analysis for the two stars identified as most likely to have been targeted, under two different observation conditions corresponding to best night at dry sea level ($k_v$ = 0.20) and average night at humid sea level ($k_v$ = 0.30), as given by Schaefer (1986; S33). The table shows the extinguished magnitudes of these stars at different altitudes, showing how they become fainter the lower they are in the sky. Using an empirical visibility cut-off at magnitude of 6, due to the fact that stars fainter than magnitude 6 are not visible to the naked eye (Kelly and Milone 2005: 56, Schaefer 1986; S33), this analysis would suggest that Hadar was visible at altitudes of 1–3°, whereas Avior and Gacrux should have been visible at altitudes of 2–4°, depending on atmospheric conditions.

For the case of some temples, such as Skorba and Ta' Ħaġrat, the apparent horizon already provides the necessary elevation to ensure that the stars would be visible when they rise. Although it has been impossible to assess the height of all temple entrances due to missing stones, it is clear that in most, if not all cases, a significant portion of the sky would be visible from them. Using data from those which allowed measurements, the average maximum altitude permitted by the entrances of Ġgantija phase temples is of about 6° (minimum of 2°, maximum of 10°), meaning that they would frame a portion of the sky sufficient to observe these stars even on an average humid night. It is therefore likely that, not only were these stars visible this low in the sky, but that the entrances of the Ġgantija phase temples framed their rising.

## Phenomenological considerations

The fact that these stars may have been targeted by the prehistoric Maltese is a curious one because these stars share a number of visual similarities that would not necessarily be shared by any other randomly picked stars. Firstly, Hadar is the eleventh brightest star in the night sky, and a very close neighbour to Rigil Kentaurus/Toliman, the third brightest star. Together these two bright southern stars are known as the Pointers, because they point towards Gacrux, the very top star of the Southern Cross which was useful for navigation (e.g. Kyselka and Lanterman 1976: 59). Gacrux and Avior have similar brightness and reddish-orange colour. They also belong to similar asterisms: Gacrux belongs to the Southern Cross constellation, whereas Avior, although technically a part of the modern constellation Carina, is also part of what is known as the False Cross asterism (Moore 2015: 185). This asterism receives its name for being easily mistaken for the Southern Cross and, although it is comprised of less bright stars, it forms a much larger configuration on the sky (Fig. 8). It is said that the False Cross caused problems for astronavigation, by being confused for the Southern Cross (Moore 2015: 185).

The resemblances between these stars continue when one considers their seasonality. Stellar motions throughout the year are such that we do not always see a given star rising and setting every night. Their dynamics can be used to divide the year into phases or stellar seasons, depending on whether or not they can be seen while rising, setting, both or neither (Brady 2015a). All three stars, after a period of not being seen in the sky (because they rise and set while the sun is still up), appear for the first time at dawn – an event known as the heliacal rising. These stars had their heliacal rising around the September Equinox (Fig. 9). Following this, the stars would rise four minutes earlier every night throughout the entire winter period until the beginning (Avior), middle (Gacrux) and towards the end (Hadar) of March, after which moment they could only be seen when setting. At some point later – early April (Avior), early June (Gacrux) or close to June solstice (Hadar) – these stars would have their acronychal setting, their last visible setting, in the evening just after sunset. After this period, they would not be seen in the night sky, their rising and setting occurring during the daytime.

**Table 6** Visibility analysis for the three stars as likely targets for the orientation of Ġgantija phase structures. The apparent magnitude of each star is shown at different altitudes and atmospheric conditions. Magnitudes in red are above 6 and, therefore, indicate altitudes at which the corresponding star is too faint to be visible

| Altitude | Hadar ($m_0$ = 0.58) | | Gacrux ($m_0$ = 1.64) | | Avior ($m_0$ = 1.86) | |
|---|---|---|---|---|---|---|
| | Dry $k_v$ = 0.20 | Humid $k_v$ = 0.30 | Dry $k_v$ = 0.20 | Humid $k_v$ = 0.30 | Dry $k_v$ = 0.20 | Humid $k_v$ = 0.30 |
| **10°** | 1.71 | 2.27 | 2.77 | 3.33 | 2.99 | 3.55 |
| **5°** | 2.65 | 3.68 | 3.71 | 4.74 | 3.93 | 4.96 |
| **4°** | 3.04 | 4.27 | 4.10 | 5.33 | 4.32 | 5.55 |
| **3°** | 3.59 | 5.10 | 4.65 | 6.16 | 4.87 | 6.38 |
| **2°** | 4.43 | 6.36 | 5.49 | 7.42 | 5.71 | 7.64 |
| **1°** | 5.83 | 8.46 | 6.89 | 9.52 | 7.11 | 9.74 |
| **0°** | 8.58 | 12.58 | 9.64 | 13.64 | 9.86 | 13.86 |

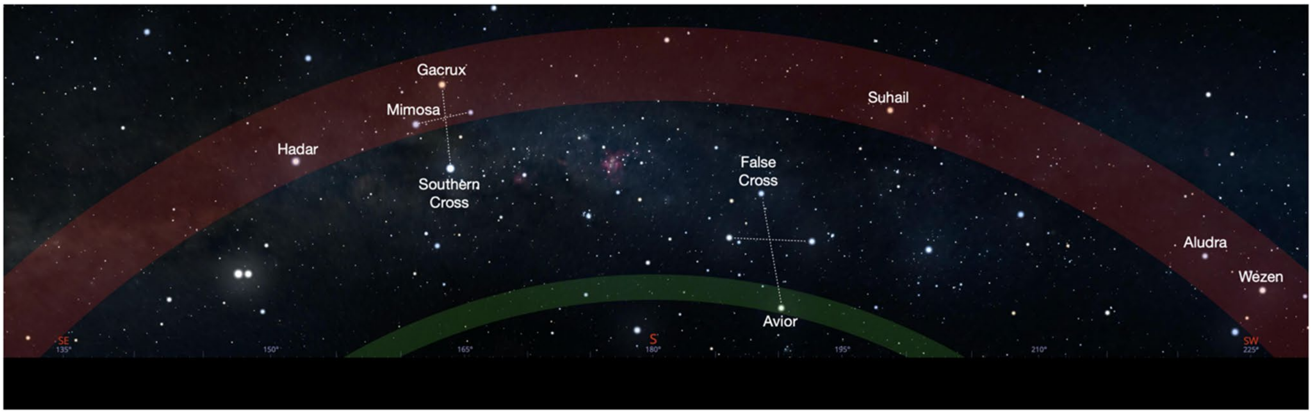


**Fig. 8** Virtual reconstruction of the low southern sky in 3250 BC when the stars highlighted by this analysis are visible. Shown are the two identified regions of significance for structures of the Ġgantija phase (red and green semi-transparent bands). Reconstruction done using *Stellarium* v24.4 (Zotti et al. 2021)

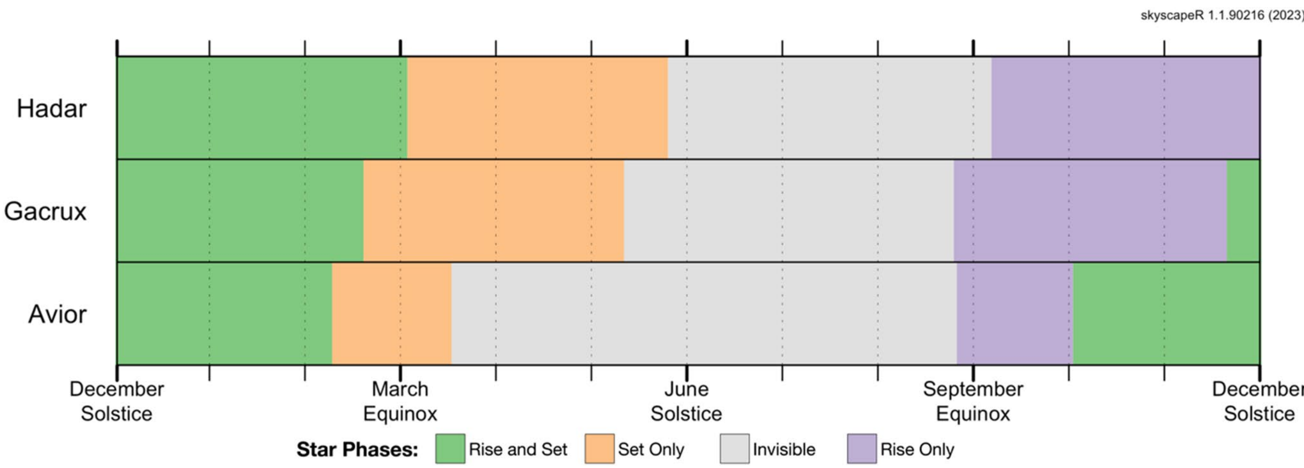


**Fig. 9** Seasonality of Hadar, Gacrux and Avior at 3250 BC. Each coloured band represents the span of time where each star can be seen at night, with different colours indicating different phases or "seasons" as per the legend. Although some variation in start date and length of each phase is expected throughout the span of the Temple period, this would have been negligible. Calculations done using *skyscapeR* v1.1 (Silva 2021)

Since their risings and settings are not visible every night in the year, any claims of alignments to these (or any other) stars therefore must be considered in light of their seasonality. We have seen before how the Ġgantija phase structures that are orientated towards these stars do so by targeting the rising positions of Hadar and/or Gacrux and the setting position of Avior. This means that the alignments could only have been observed roughly from September equinox to March equinox, in the cases of Hadar and Gacrux, or from late October to early March, in the case of Avior. In other words, the alignments only occurred in the winter half of the year.

It is worth considering the cases of Ta' Ħaġrat and Skorba where there are two structures, each aligned with one of the identified stars. Although all structures belong to the Ġgantija period, Ta' Ħaġrat West and Skorba West (the leftmost structures in each panel of Fig. 10) are believed to be older than their East counterparts. This, at least in the case of Ta' Ħaġrat, would indicate that the East structure was not meant to visually align with the setting of Avior, since the West structure blocked any line of sight. On the other hand, the alignment of Skorba East was still viable.

On the other hand, the other three Ġgantija phase structures with alignments to Avior (Mnajdra East, Ħaġar Qim Room 13 and Kordin III East) are all suggested to have been the earliest structures in their respective complexes – perhaps with the exception of Ħaġar Qim Room 13 (Trump 2002: 137, 142, 148). This may suggest an earlier interest in Avior, which was superseded by the Gacrux/Hadar complex. Tarxien South and East are the outliers of this group since, even though Tarxien East likely predates the other two structures in this complex, Tarxien South is clearly the most recent. Tarxien South may therefore represent a return

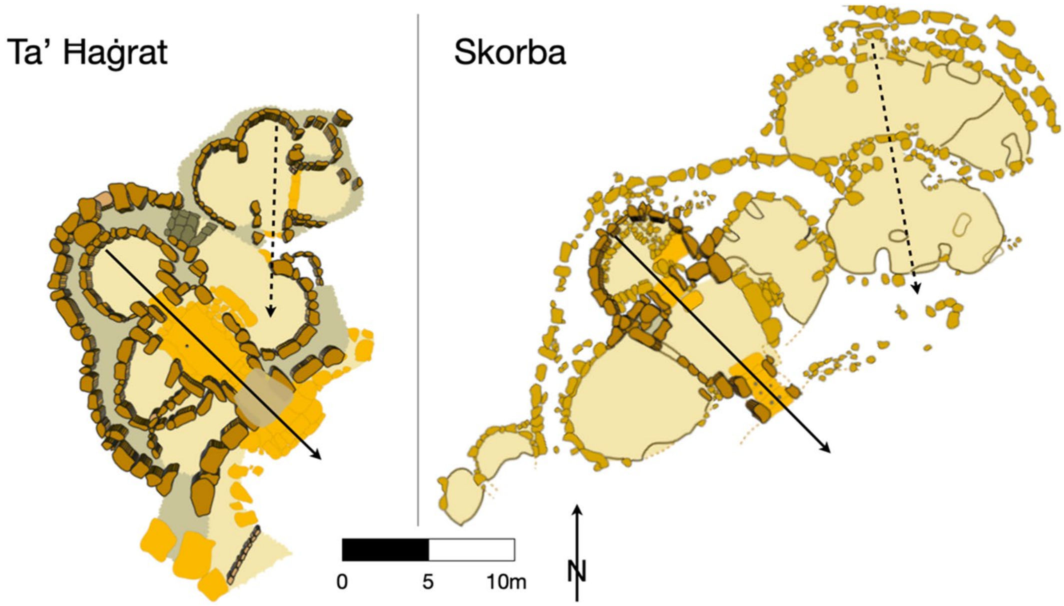


**Fig. 10** Plans of the Ta' Ħaġrat (left) and Skorba (right) temples, showing the orientation of the earliest (solid arrow) and the later structures (dashed arrows). Plan after Cilia (2004)

to a much earlier tradition of orientation to the setting of Avior.

## Navigating by the stars

We may never be able to fully discern whether the prehistoric Maltese were intentionally targeting either Hadar, Gacrux, both, the entire Centaurus-Crux complex, or whether Avior was intentionally targeted, or was a fluke. Nor may we ever fully understand the meaning or purpose these stars held for the prehistoric Maltese, nor the reason behind the building of so many structures aligned to them during the Ġgantija phase of the Temple period. However, we can experiment with informed speculation.

The first observation to make is that all three identified stars have been used in historical times as navigational stars, recognised in *The Nautical Almanac* – an annual publication by HM Nautical Almanac Office (in Great Britain) and the US Naval Observatory (in the USA) where the positions of selected celestial bodies are given to enable navigation through celestial observation. Their usefulness for navigation extends far back in time with the Southern Cross being used by Spanish and Portuguese sailors for determining the position of the south pole (van Gent 2006, p. 211). Furthermore, the Southern Cross is also used for celestial orientation in South American indigenous cosmological systems (Urton 1981, p. 59).

A number of factors lead us to speculate that the main function of these stars in the Temple Period was navigational, and that it was this purpose that elevated them to cosmological status. Firstly, we need to consider the geographical nature of Malta. As an archipelago comprised of three large islands and eighteen smaller ones, at least two of which have evidence of prehistoric occupation, seafaring was clearly necessary to move people and products across the islands. Furthermore, the earliest evidence for human occupation indicates the colonists came from Sicily and that, in the Temple Period, exotic goods were being imported from Sicily, Lipari and Pantelleria (Trump 2002: 38; Grima 2011: 13). This further stresses the importance that navigating in open sea, with no line of sight to their destination, especially in the return trip south back to Malta, must have had. A final piece of evidence comes from the iconography of the Temple Period, with depictions of fish and running spiral motifs possibly representing the sea being commonplace (Grima 2001).

As mentioned above, we are not the first to suggest this (e.g. Cox 2001; Barratt 2022). However, previous explanations linking Gacrux, or the Southern Cross, with navigation have been unsatisfactory as they do not actually address, or explain, the need or intention to align the megalithic structures to this constellation, which can be used for navigation regardless of whether a structure is built in alignment with it. What these explanations have done is use the observed alignment to infer the potential cosmological significance of this star or constellation for broader Maltese society. However, this still leaves the question of why they went to the effort of building these structures in alignment with said star unexplained.

We propose that, given the above analysis and discussion, it is possible that the Maltese temples, in addition to other cosmological, religious or social roles that they may have had (e.g. Lomsdalen 2022; Barratt 2022), could have also been used to train or teach navigation-by-the-stars to younger generations. Pupils may have been placed in the back apse of the temple, looking out towards its entrance. The sunken floor of the court in front of them, if indeed it had been naturally or artificially flooded as has been proposed, would have reflected the stars that could be seen through the entrance as well as the stars above. The megalithic structure, set up in this way, would mirror the conditions of being in a boat in open sea at night, with nothing but the stars to help one navigate. This simulated environment would differ in one key characteristic: the horizon was largely blocked by the temple uprights, with the exception of the entrance, which framed what must have been the most important section of the night sky to memorise – the section with the stars that indicate the southerly directions that they would need to return home after a trip north to Sicily, Pantelleria or Lipari. As has been argued elsewhere, a trip north to Sicily, under ideal weather conditions, could be done during the day without the need for a navigational aid by merely following the view of Mount Etna and the Hyblaean Hills on the southeast coast of Sicily (Grima 2011: 14–15). The return trip, on the other hand, would be much more hazardous since none of the Maltese islands can be seen from Sicily. It is this return journey that could benefit from the visual aid to navigation that the stars could provide, and therefore a most important aspect to teach new navigators.

Not all temple entrances allowed the observation of the entire Southern Cross rising, quickly followed by the two bright Pointers of Centaurus. It is therefore more likely that the pupils would be looking to memorise what have been called 'starpaths' or 'linear constellations' – lines of stars that rise at roughly the same azimuth and that therefore can provide a steady orientation for several hours throughout the night (Kursh and Kreps 1974; Brady 2015b). This is a well-known feature of Polynesian and Micronesian navigation, where a specific stone arrangement known as a 'stone canoe' is used to teach starpaths that mark the directions of other islands in a way not dissimilar to what we are proposing here (Lewis 1974). In fact, a peculiar stone found in Kordin III may very well be a stone representation of a canoe (Trump 2002: 137, Cilia 2004, 95). A similar explanation has also been proposed for navigation in the East Mediterranean by Bronze Age Minoans (Berio 2022). Observing the sequential rising of bright stars is something that has already been suggested for prehistoric Malta, with regards to the already mentioned Mnajdra tally slabs (Ventura et al. 1993; Agius et al. 2021). Indeed, the list of stars identified by our analysis, especially for the most significant region (Table 5), show a sequence of stellar risings starting with Wezen, then Suhail, Gacrux, Mimosa and finally Hadar which could have performed the function of a starpath (see stars within red band in Fig. 8). Having this region of the sky completely framed by the temple entrances would certainly help learn these stellar sequences.

Finally, the disappearance of these orientations from the structures built in the Tarxien Period could indicate that the previous temples were still in use for this purpose, that there was a change in navigational technology, or perhaps that new navigational routes, requiring other starpaths to be memorised, were opened in this phase.

## Concluding remarks

We have endeavoured to take a fresh statistical look at the question of the orientation of a typologically and geographically well-constrained prehistoric monument – the so-called Maltese Temples. Previous approaches to this question have either proposed explanations without any formal analysis, have only looked to disprove randomness or jumped into celestial interpretations without first exploring topographical ones. By contrast, the approach we have taken here employed a single statistical framework that allowed us to test the data against a variety of hypotheses, whether terrestrial or celestial. This extension of Silva's (2020) probabilistic framework and significance test allows not only to test orientation data against the null hypothesis of random orientation, but also against any other hypotheses that can be modelled as a probability distribution – such as orientation following the terrain, wind direction, river direction, etc. This not only fulfils Ruggles (2011) call for a closer engagement between landscape and skyscape archaeology but, in the process, opens up this exciting, and often speculative, field of archaeology to a new era of methodological rigour.

This methodology was deployed on a new set of measurements, with associated uncertainties, of the orientation of 32 structures – the largest sample ever analysed. The results of this statistical analysis can be summarised as follows. Firstly, despite most temples having orientations that can be explained either by chance, terrain aspect, protection from wind or winter sunlight, there are some patterns of orientation that cannot be explained by any of the above. Secondly, these patterns are only statistically significant for temples of the earlier Ġgantija phase (3400–3100 BC). Therefore, our results add fuel to the discussions around the possibility of significant social change between the Ġgantija and Tarxien (2800–2400 BC) phases of the Temple Period. And thirdly, that the two statistically significant orientation clusters matched the rising or setting of the stars Hadar, Gacrux and Avior. Our analysis, therefore, confirms previously suggested alignments to Gacrux, while adding Avior and Hadar to the mix.

It was argued that these stellar matches were unlikely to be coincidences. All three stars inhabit the same region of the night sky. Two of them – Gacrux and Avior – have similar brightness, colour and feature in similar asterisms – the Southern Cross and the False Cross, respectively – which are known for being confused one with another. Hadar is also often used as a pointer to identify the Southern Cross, thereby connecting all three stars. The important role of these stars and asterisms for sea navigation for a number of societies has been discussed and it is suggested that these stars may have played a similar role for the Neolithic Maltese. However, such interpretations only account for the importance of the celestial object for the culture and do not answer the stricter question of why the Temples were built to align with these stars. We proposed that the temples, in addition to other, more traditionally symbolic and/or social purposes, may have acted as places of instruction for young seafarers to learn these important navigational stars. Without a clear understanding of how these stars, or the starpaths they belonged to, would have been used by the prehistoric Maltese for navigation, and a better understanding of how the inner spaces of the Temples were used, our hypothesis will however remain speculative. Nevertheless, we think its proposal casts new light, and raises new questions about these structures and broader prehistoric Maltese society. As the Stoic philosopher Seneca put it "non est ad astra mollis e terris via" (Sen. *Her. F.* 437) – there is no easy way from the earth to the stars. That may very well be why the Temples were aligned to the stars: to point the way.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s12520-025-02208-4.

**Acknowledgements** The authors would like to thank Reuben Grima, Frank Ventura, Mario Vassallo and Tim Darvill for the many insightful discussions surrounding the present topic; Andrew Smith for assistance with processing DTM data to construct horizon profiles; and two of the anonymous reviewers whose attention to detail and kind words of encouragement have improved this article immensely. Any errors, omissions or erroneous interpretations remain the authors' sole fault.

**Author contributions** F.S. and T.L. conceived the main research question. T.L. did the data gathering. F.S. and T.L. worked on the statistical analysis. F.S. wrote the main manuscript text. All authors contributed to the creation of the figures and reviewed the manuscript.

**Data availability** All datasets used in this study are available as supplementary information.

## Declarations

**Competing interests** The authors declare no competing interests.



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