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The effects of blank size and knapping strategy on the estimation of core's reduction intensity

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Abstract

The intensity of reduction on lithic assemblages has implications in the understanding of hominin behaviors such as mobility patterns, type and intensity of occupations, raw material management and cognitive abilities, as well as in the formation of lithic assemblages. In the last decades, numerous methodological proposals have been developed aimed at estimating the reduction intensity in retouched tools and cores. Regarding the analysis of the reduction in cores, several studies have focused on technical parameters, in many cases without considering the different reduction strategies used. In this paper, we present the results of a sequential experimental program aimed at evaluating the effect of two different reduction strategies (unifacial unipolar and bifacial multipolar centripetal), as well as the size of the original nodules, in the estimation of the intensity of reduction on cores. Our results show that both, the core reduction strategies and the size of the nodules, affect the estimation of reduction intensity. Therefore, we pose the necessity of considering a series of aspects, such as the perimetric development and faciality of the exploitation, as well as the size of nodules, to more accurately infer the intensity of reduction in cores.

Keywords Lithic reduction · Reduction intensity · Cores · Knapping strategy · Blank size · Paleolithic

Introduction

Every process of lithic knapping is a reduction process, in which a blank with certain initial mass and volume progressively loses both properties until the moment it is discarded. Therefore, it is possible to measure this reduction in quantitative terms.

The quantification of reduction in lithic artifacts is important for the correct interpretation of the lithic assemblages. The composition of a lithic assemblage cannot be understood without considering the cultural formation processes, the use-life of the artifacts that comprise it (the amount of time that each piece was used), and the curation (the relationship between the utility used and maximum utility of each piece), since these aspects can influence the presence of and frequency with which the different artifacts appear in the archeological record (Schiffer 1987; Shott and Sillitoe 2005).

Numerous researchers have studied the relationship between lithic technology, mobility, and availability of raw materials in hunter-gatherer societies (Andrefsky 1994; Blades 2003; Morales 2016; Schiffer 1987). Several studies have shown the influence of variables such as use-life of the tools, mobility patterns, the type, intensity and duration of occupations, the site function, the availability and quality of raw materials as well as the transportation of materials and management of landscape in the formation, composition, and distribution of the lithic assemblages (Andrefsky 1994; Carr and Bradbury 2011; Kuhn 1990; Li et al. 2016; Nelson 1991; Rolland and Dibble 1990; Schiffer 1987). Many of these aspects are not directly visible from the archeological record. However, stone tools, because of their imperishability and because they are a material reflection of raw material procurement and management, offer—through reduction analysis—a

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way to approach these behavioral patterns from the archeological record (Morales et al. 2015).

The effects of reduction on the final morphology of the artifacts have been studied in a variety of tool classes, such as handaxes (Ashton 2008; Iovita and Mcpherron 2011; Shipton and Clarkson 2015a), scrapers (Kuhn 1990; Morales et al. 2015; Shott 1995; Shott and Weedman 2007), tanged tools (Iovita 2011), or backed blades (Muller et al. 2018). The demonstration of the so-called Frison effect (Jelinek 1976), which describes how the shape and use of stone tools change through retouching, is a major outcome of this research line and argues against the excessive discretization of tool types on the basis of shape and integrating most of this variability on a continuum of reduction (Dibble 1987; Morales 2016). This shows that the degree, or intensity, of reduction of lithic artifacts has major implications for both the formation and typological variability of lithic assemblages.

Over the last three decades, several methodological approaches have been proposed to quantify the degree of reduction of lithic assemblages from different perspectives, either in absolute or relative terms. Among these, the most common approaches have been the study of tool reduction intensity, in the study of retouched edges (Andrefsky 2006; Clarkson 2002; Dibble 1987; Eren et al. 2005; Eren and Sampson 2009; Hiscock and Clarkson 2009; Kuhn 1990; Marwick 2008; Morales et al. 2013; Shott 1995; Shott and Weedman 2007), or the estimation of the size or shape of the original flake prior to retouching from the dimensions of the percussion platform and/or the exterior platform angle (Braun et al. 2008; Clarkson and Hiscock 2011; Dibble and Pelcin 1995; Dogandžić et al. 2015; Lin et al. 2013; Muller and Clarkson 2014; Pelcin 1998; Shott et al. 2000).

The study of the reduction intensity in cores is an ideal complement to these studies of tool reduction intensity (Braun et al. 2006; Douglass et al. 2017), since it is important to consider that core reduction and tool reduction do not reflect exactly the same thing. While the study of tool reduction evaluates the level to which flakes were retouched and resharpened, used, or reused (Blades 2008), the study of core reduction seeks to quantify the degree to which a nodule was exploited, or, in other words, the extent of flake production from a core. Therefore, although they often can provide similar information (e.g., availability and management of raw materials, mobility patterns, etc.), they also provide different levels of information because they are two different processes. For example, core reduction estimation can assess the degree to which a given raw material or a specific core reduction strategy is integrated into the technological structure, while the intensity of retouching provides information about the amount of morphological configuration and/or resharpening that the blanks obtained through core reduction have undergone, that is, their use-life (Blades 2008).

This paper presents the results of an experimental program aimed at evaluating the influence of different flaking strategies and the original size of the nodules on the correct estimation of the amount of reduction in cores.

Background

Although core reduction is a less explored research line, according to the literature, the relationships between different variables and attributes have been investigated as potential estimators of a core's reduction extent. Among these, the most well-studied relationships are the ratio of the number of flakes to the number of cores (Dibble 1995a; Roth and Dibble 1998), the number of scars present in each core (Bradbury and Carr 1999; Douglass et al. 2017; Ingbar et al. 1989; Shott 1996), the number of rotations as reflected in the number of percussion platforms and/or exploitation surfaces (Braun et al. 2006; Douglass et al. 2017), the number of convergences of exploitation surfaces, the angular relationship between the percussion platforms and the exploitation surfaces, the dimensions or mass of flakes and cores (Key and Lycett 2014; Key and Lycett 2015; Prasciunas 2007), the number of step terminations in each core, the amount of cortex remaining on flakes and cores (Dibble et al. 2005; Lin et al. 2010), and the percentage of non-cortical surface (Douglass et al. 2017; Magne 1989; Magne and Pokotylo 1981) or the flaked area index (FAI) (Li et al. 2015).

Additionally, different technological attributes considered in the aforementioned studies have been experimentally combined, and several statistical models have been designed with the aim of inferring the intensity of core reduction in archeological assemblages (Douglass et al. 2017). Finally, indexes of core reduction intensity have also been established, such as the flake scar density (Shipton 2011) or the scar density index (SDI) (Clarkson 2013), which consist of dividing the number of scars by the surface of the cores, either by calculating the core area (length by width) (Shipton 2011) or by quantifying the surface using 3D models (Clarkson 2013). The SDI is based on one premise: as the reduction of a core progresses, the surface of the core decreases and the number of scars increases.

Each core recovered from the archeological record is the result of the combination of a given initial morphology of a nodule and certain morpho-volumetric management developed through knapping. This morpho-volumetric management can be carried out through different knapping strategies and methods, meaning that both morphological and volumetric changes in the core are produced in different ways and thus affect the parameters or technical attributes available for analysis (e.g., superposition of scars, generation and elimination of percussion platforms, etc.).

Therefore, it is possible that parameters traditionally used as indicators of the amount of reduction can be significantly influenced by the different knapping strategies carried out during the reduction of the core. This may include parameters such as the number of exploitation surfaces and percussion platforms or the number of convergences between exploitation surfaces, which are based on the assumption that as the reduction advances, the number of core rotations increases, thereby increasing the number of exploitation surfaces and percussion platforms and, by extension, the number of convergences between exploitation surfaces (Douglass et al. 2017). However, although in multifacial multipolar exploitation strategies (e.g., spheroids or polyhedral), the rotations or number of percussion platforms probably reflect a greater degree of reduction; in general, this factor is intrinsically related with the type of core reduction strategy, since rotations are not always necessary and do not always increase as the reduction progresses.

SDI is perhaps the most explored estimator of core reduction, and although it has been tested in experimental and archeological assemblages (Clarkson 2013; Clarkson et al. 2014; Ditchfield 2016; Groucutt et al. 2015; Li et al. 2015; Shipton and Clarkson 2015b), it presents a series of drawbacks that must be considered. First, despite being reduced intensively, nodules with a larger original size can derive into cores with a lower density of flakes per surface area than those initiated on smaller nodules (Douglass et al. 2017). Second, smaller cores are more prone to suffer an overlapping of new scars over existing ones, causing the number of scars visible in the core to oscillate cyclically as the reduction progresses (Clarkson 2013).

For these reasons, both the size and shape of the nodules, as well as the application of specific reduction methods and strategies, are treated in this paper as analytical variables in order to evaluate how they affect the estimation of the reduction intensity from the different methodologies proposed in the literature.

Materials and methods

To carry out the experiment, we used 30 quartzite nodules from Olmos de Atapuerca (Burgos, Spain). The nodules were ordered by size based on their mass and surface area, and using a paired-group cluster analysis, they were divided into three groups of ten nodules (small, medium, and large, with a mass ranging from 230.2 to 3968.4 g and a surface area ranging from 874.2 to 15,025.1 cm^2). Two knapping strategies, bifacial multipolar centripetal (BMC) and unifacial unipolar (UU), were applied to five nodules from each size group, so that 15 cores were obtained with BMC reduction and another 15 with UU reduction.

These core reduction strategies were chosen because they present very different volumetric organization and management, which generate a different morpho-volumetric evolution throughout the reduction process. The BMC strategy consists of the reduction of two opposite faces of the blank, removing flakes both in alternate or alternating way following a perimetral scheme along the edge of the core, while the UU strategy is performed on a single surface, with the flake scars running unidirectionally along the thickness of the blank (see Fig. 1).

These two types of core exploitation are very frequent throughout the Paleolithic, both temporally and geographically, having been documented from the first mode 1 industries until the Holocene (Davis et al. 2012; de la Torre 2011; García-Medrano et al. 2015; Ollé et al. 2016; Stout et al. 2010).

To perform the experiment, a sequential protocol was followed. All the initial nodules were measured, weighed, and 3D scanned before the beginning of the experiment so that the initial parameters of mass, surface area, and volume were available. During the experiment, each knapping sequence was interrupted every two flake removals (longer than 20 mm) for measurement, weighing, and the realization of new 3D models of each core.

Due to differences in the size of the nodules, six phases of two flake removals were made for the small cobbles group, resulting in 12 flake removals per core. For the medium and large groups, ten phases were made, resulting in 20 flake removals for each core. In this way, starting from 30 initial nodules, 260 cores were obtained at different reduction moments (130 BMC and 130 UU) and a total of 520 flakes. All of them were knapped through freehand hard hammer percussion by one of the authors, J.R.R., using different quartzite hammers.

The three-dimensional models were obtained through the Breuckmann SmartSCAN3D-HE Scanner with a 250-mm field of view (Breuckmann Optocat 2012 R2-2206 software). From the 3D models, the maximum dimensions (mm), the surface area (mm^2), and the volume (mm^3) of each object were calculated using MeshLab software. The 260 3D models were treated to repair the meshes in order to maintain the original shape of the cores. All 3D models resulting from this experiment are available for scientific or educational purposes at https://doi.org/10.5281/zenodo.2585423 (Lombao and Rabuñal, 2019).

Regarding the parameters analyzed, we have selected those used by various authors in previous studies:

– Mass. The result of any lithic knapping process is a continuous decrease in size and mass. Some studies have quantified the mass of flakes and cores with the objective of testing this variable as a reduction estimator (Marks et al. 1991; Marwick 2008). Each core was weighed (in grams) at the end of each phase with the aim of analyzing whether mass is a variable with inferential capacity for the reduction intensity estimation.
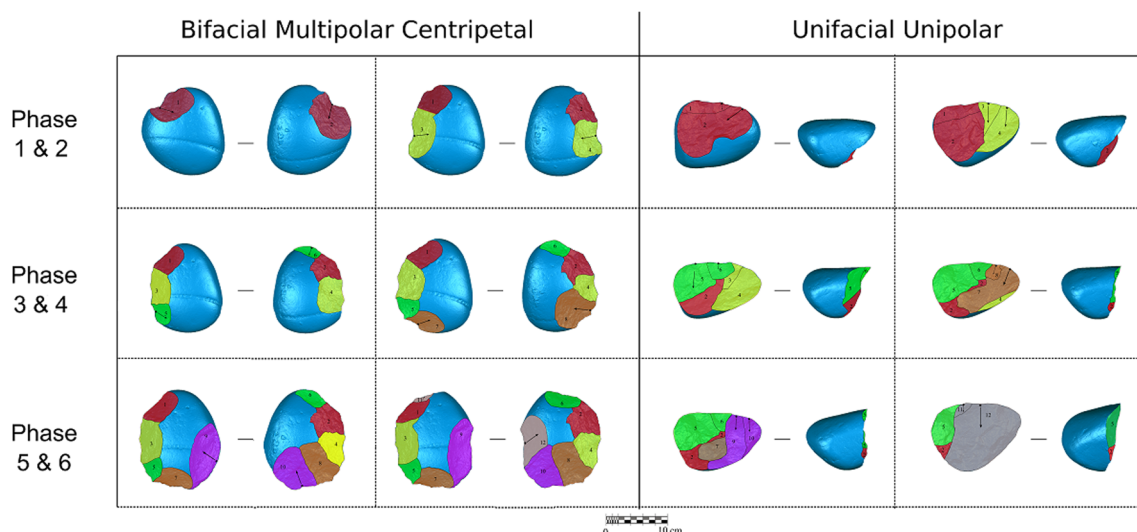
Fig. 1 Sequential reduction of both types of cores

- Number of scars. Numerous studies suggest that there is a relationship between the number of scars present in the cores and the intensity of the reduction (Bradbury and Carr 1999; Douglass et al. 2017; Ingbar et al. 1989; Shott 1996; Stout et al. 2010) since the more reduced a core is, the more flakes have been removed. Therefore, it is assumed that at a greater intensity of reduction, a greater number of scars should be present on the core. Related to this, we have differentiated between two variables: first, the number of real flake removals, those that occurred from the beginning of the reduction until the moment of control after each knapping phase, and second, visible scars that remained on the surface of the cores, to check how the overlapping of scars affects the estimation of the reduction. To count the visible scars in each series more precisely, counting was done by refitting the flakes onto the cores.

The SDI (Clarkson 2013) consists of the relationship between the number of scars and the surface of the core, following the assumption that, as the reduction increases, there is an increase in the number of flake removals and a decrease in the core surface. Therefore, high SDI values correspond to high degree of reduction and vice versa. With the aim of evaluating the operation of this method under ideal and real conditions, we calculated two variants of the SDI: the "real" scar density index (RSDI), which accounts for the total real flake removals and the "visible" scar density index (VSDI), which exclusively counts the visible scars (longer than 10 mm) on the surface of the cores after each reduction phase. In this way, the effect of scar overlapping on the quantification of the reduction degree can be tested.

The percentage of non-cortical surface, or FAI (Li et al. 2015), was obtained by dividing the non-cortical surface area

by the total surface area of each core. It is based on the premise that as the reduction progresses, the flake removals will progressively remove more of the cortex. The quantification of cortical and non-cortical surfaces has been done through 3D models, since it allows them to be measured with greater precision (Lin et al. 2010).

Regarding statistical procedures, we first carried out exploratory analyses by applying the Shapiro-Wilk W (p) normality test to establish the distribution of the data. We applied Mann-Whitney U tests to determine if there were statistically significant differences in the medians and Kolmogorov-Smirnov (K-S) tests to compare the distribution of the values obtained through the different parameters analyzed for each type of core reduction strategy and the size of the original blank.

We then applied correlation tests to both types of core reduction strategies together and separately in order to evaluate the relationship between the increase in values obtained by each method and the decrease in the remaining mass as the reduction progressed. Following previous studies (Clarkson 2013; Hiscock and Clarkson 2009), we used the coefficients of determination (r^2) to evaluate the strength of the inferential capability of these correlations, since this statistical test expresses the magnitude of the effect of the change that occurs in the percentage of remaining mass on the value of each index (Hiscock and Tabrett 2010).

To check the incidence of the size of the original blank on the different parameters obtained, we carried out ANCOVAs. The regression lines were compared when studying the interaction of the size of the blanks with the percentage of remaining mass. To do this, we created two models, the first considered the existing interaction between the original size of the blanks and the percentage of remaining mass, and the second eliminated this interaction. Then, we carried out an ANOVA comparing both models to test if the suppression of the size

interaction significantly affected the model. All statistical procedures were carried out in R (R Core Team 2015).

Results

Once the reduction phases were completed, BMC and UU cores were reduced in a similar way (Table 1). Percentages of extracted mass varied between 1.81% in the first phase of reduction and 92.13% in the final phase for the UU cores and between 4.43% and 86.96% for the BMC cores. Both cases followed a non-parametric distribution (Shapiro-Wilk $(p) < 0.05$). Neither set presents statistically significant differences in the level of reduction between the two strategies, either in the mean values (M-W $(p) = 0.08$), or in the distribution of the values (K-S $(p) = 0.15$). Figure 2 illustrates the evolution of the reduction after each phase for each type of exploitation.

Mass

By relating the values of the final weight of each core along the sequence with the percentage of their remaining mass, we obtained a coefficient of determination of $r^2 = 0.22$ in the BMC cores and $r^2 = 0.42$ for UU cores. When both reduction strategies under the same regression were combined, an intermediate r^2 was obtained ($r^2 = 0.32$).

Number of flake removals and flake scars

Concerning the real number of flake removals and visible scars on the cores, two different aspects were analyzed. First, we examined the correlation between the number of real removals and visible scars on each core with the percentage of remaining mass, in order to observe the inferential potential of these variables on the amount of reduction. Second, we assessed the correlation between the number of flakes produced and the number of visible scars, since, although it is logical to expect that as the reduction progresses the number of scars on the core will increase, new removals can overlap previous scars, affecting the number of visible scars on the surface of the cores.

Regarding the first question, the relationship between the number of real flake removals per core and the percentage of remaining mass resulted in $r^2 = 0.69$ for UU cores and $r^2 = 0.50$ for BMC cores. These values are remarkably higher than those obtained by analyzing the number of visible scars, where the results are $r^2 = 0.40$ for UU cores and $r^2 = 0.48$ for BMC cores. Moreover, while the correlation level is maintained when combining both core reduction strategies in the same analysis for the real flake removals per core ($r^2 = 0.59$), this coefficient drops considerably when analyzing the number of visible scars ($r^2 = 0.21$), which indicates a different performance of these variables as the reduction progresses.

When comparing the relationship between the number of flake removals per core and the percentage of mass remaining according to the size of the initial blanks, for the BMC cores, we obtained very similar values for the large and medium blanks ($r^2 = 0.58$ and $r^2 = 0.54$, respectively) and a slightly lower value in the case of small nodules ($r^2 = 0.39$). For the UU cores, those made on medium- and small-sized formats have very high coefficients of determination ($r^2 = 0.84$ for both sizes) compared with large formats ($r^2 = 0.55$).

Concerning the relationship between the number of visible scars and the percentage of remaining mass, for BMC cores, the values of coefficient of determination are lower than 0.5, except for the medium-sized blanks ($r^2 = 0.56$). In the case of UU cores, small blanks have a lower coefficient of determination ($r^2 = 0.29$) compared with medium and large blanks ($r^2 = 0.47$ and $r^2 = 0.37$).

Regarding the latter, the scars' overlapping affects differently depending on the reduction strategy (see Fig. 3). On BMC cores, there is a strong correlation between visible scars and real flake removals ($r^2 = 0.94$), which indicates a low level of information loss as the reduction progresses. In the case of UU cores this does not happen, since in the most advanced phases, the new removals eliminate the previous scars resulting in a significantly lower value ($r^2 = 0.58$).

In addition, the size of the original blanks influences the scars' overlapping according to the type of core reduction strategy. On the BMC cores, this effect is not significant for the three size groups, while on the UU cores, the coefficients of determination are notably lower, especially in small-format

Table 1 Results of each reduction strategy group according to original blank size

Core reduction strategy	Bifacial multipolar centripetal			Unifacial unipolar		
Blank size	Large	Medium	Small	Large	Medium	Small
Number of samples	50	50	30	50	50	30
Percentage of extracted mass (mean)	53.35	43.83	42.21	51.13	56.56	45.32
Percentage of extracted mass (min)	4.62	4.43	13.01	1.81	2.45	7.22
Percentage of extracted mass (max)	84.80	86.96	75.28	84.80	92.13	73.73
SD	21.86	23.92	19.34	25.34	27.19	19.70
Coeff. var.	40.98	54.58	45.81	49.56	48.07	43.46
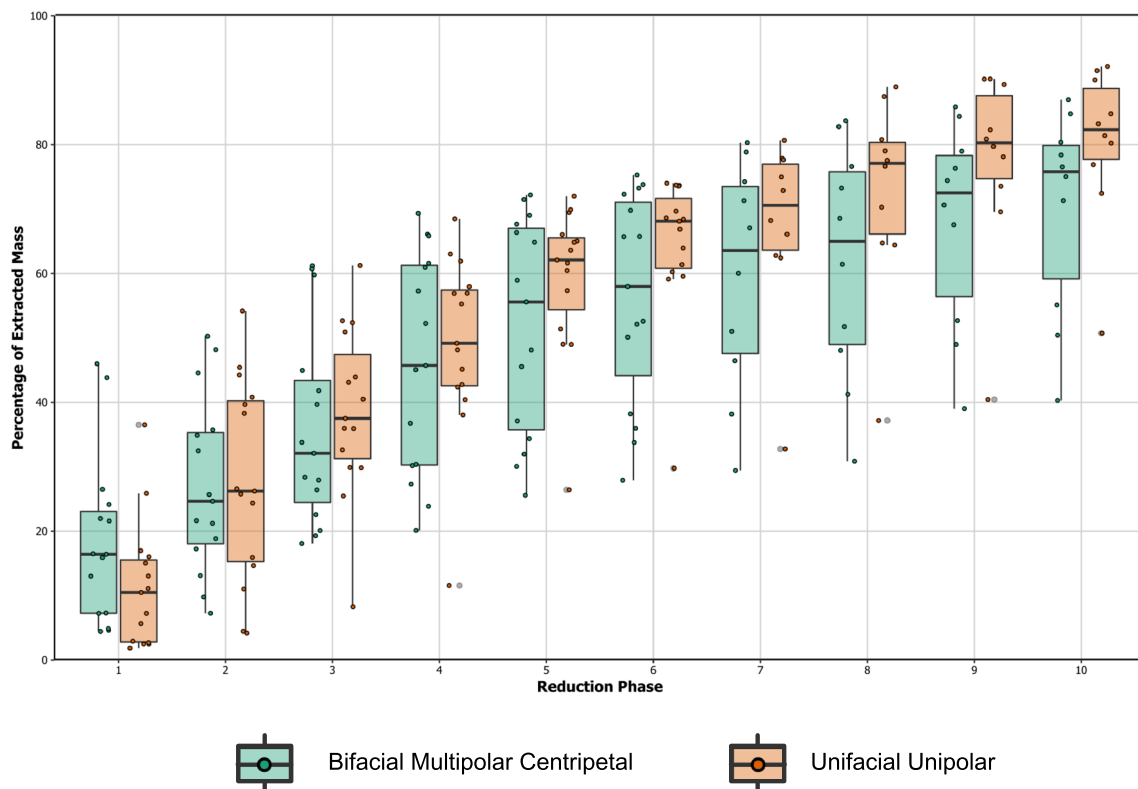
Fig. 2 Box and jitter plots of percentage of extracted mass for each reduction phase in the two reduction strategies

cores (small blanks $r^2 = 0.40$; medium blanks $r^2 = 0.55$; large blanks $r^2 = 0.60$).

Scar density index

Once we verified that there is a different process of information loss in relation to each reduction strategy, it would be expected that other parameters depending on the scar visibility, such as the SDI, are influenced by this overlapping effect of scars too.

The values of the SDI and the percentage of the remaining mass were converted to a logarithmic scale of base 10 to obtain linear correlations (Clarkson 2013). In this way, the RSDI of both core reduction strategies combined in the same linear regression provided a correlation of $r^2 = 0.60$. However, we found differences within each strategy, since for BMC cores, the value is $r^2 = 0.47$, and for the UU, it is $r^2 = 0.69$.

As far as the influence of the size on the RSDI is concerned, similar values of the coefficient of determination were obtained for the BMC cores in all blank sizes (small $r^2 = 0.60$, medium $r^2 = 0.63$, and large $r^2 = 0.65$). In the case of UU, we obtained different values according to blank size (small $r^2 = 0.85$, medium $r^2 = 0.83$, and large $r^2 = 0.68$).

Using an ANCOVA, we compared these three regression lines for each reduction strategy by testing the effect of the size of the original blank on the RSDI, while controlling the effect of the percentage of remaining mass. We compared regression

lines to assess the interaction between the size of the blanks and the percentage of remaining mass, and there appears to be an interaction between the two factors when the effect of one of them on the dependent variable is not the same at every level of the other factor.

For the BMC cores, the results of the first model show a significant effect on the size and percentage of remaining mass ($p = 0.00$), but the interaction between both is not significant ($p = 0.60$). In the second model, the size did significantly affect the real SDI ($p = 0.00$). The ANOVA comparing both models indicated that the suppression of the size variable did not significantly affect the model ($p = 0.60$). In this case, the slopes of the correlations behave similarly in the three size nodules, though they have different intercepts with respect to the y-axis (RSDI). The group of small blanks presents the largest intercept, while the large blanks have the lowest intercept (see Fig. 4). That means that given the same moment of reduction (x-axis), the RSDI is higher in the cores made on small blanks and lower in the cores made on larger blanks.

In the case of UU, the results of the first model show a significant effect of size and percentage of remaining mass ($p = 0.00$), as well as in the interaction between both ($p = 0.02$). In model 2, size significantly affected the dependent variable (in this case, RSDI) ($p = 0.00$), indicating differences in the intercepts of the regressions of the different sizes.

The result of the ANOVA ($p = 0.02$) shows that the interaction between both variables significantly affects the model.
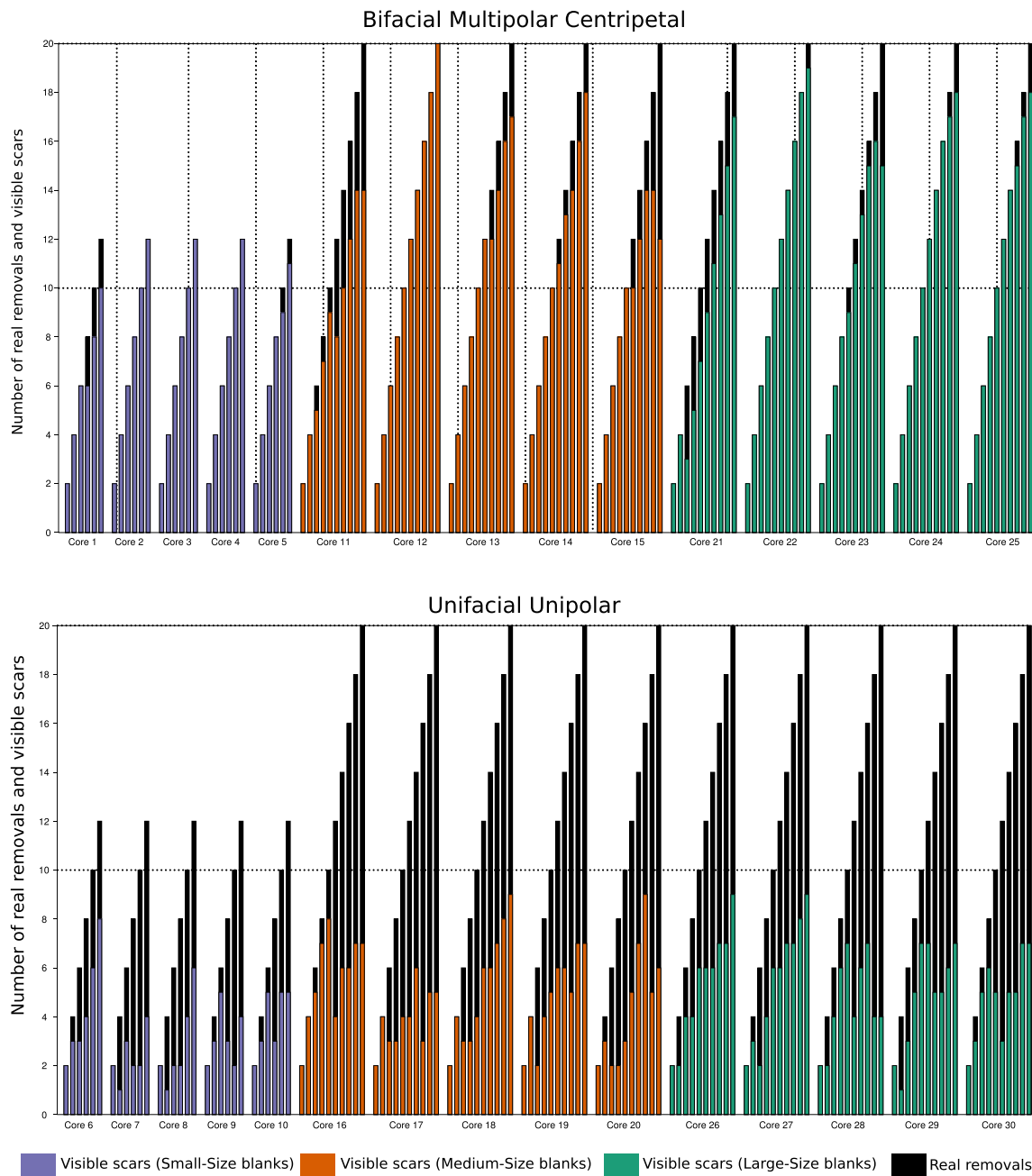
Fig. 3 Relation between number of real flake removals and number of visible scars on core for each core and phase. Upper: BMC cores; lower: UU cores

The different sizes have different slopes and, in addition, present different values in the intercepts. In this way, we observe a steeper slope in the case of small-sized cores; that is, as the reduction progresses, the RSDI grows to a greater extent than in the other two blank sizes (see Fig. 4).

When the VSDI was analyzed, similar values for both methods were obtained, $r^2 = 0.45$ in the BMC cores and $r^2 = 0.57$ in the UU cores. However, when the two core reduction strategies were combined, the correlation of the visible VSDI has a lower coefficient ($r^2 = 0.41$) (see Fig. 5).

The results of the Mann-Whitney and Kolmogorov-Smirnov tests indicate that for the RSDI, there were no statistically significant differences either in the mean values (M-W (p) = 0.11) or in the distribution of the values (K-S (p) = 0.15) between strategies. However, there are statistically significant differences on the VSDI between core reduction strategies, both in the mean values (M-W (p) = 0.00) and in the distribution of those values (K-S (p) = 0.00). This means that the differential effect of the overlapping of the scars according to the type of core reduction strategy affects the performance of this index, resulting in statistically significant differences among assemblages whose reduction is statistically similar.
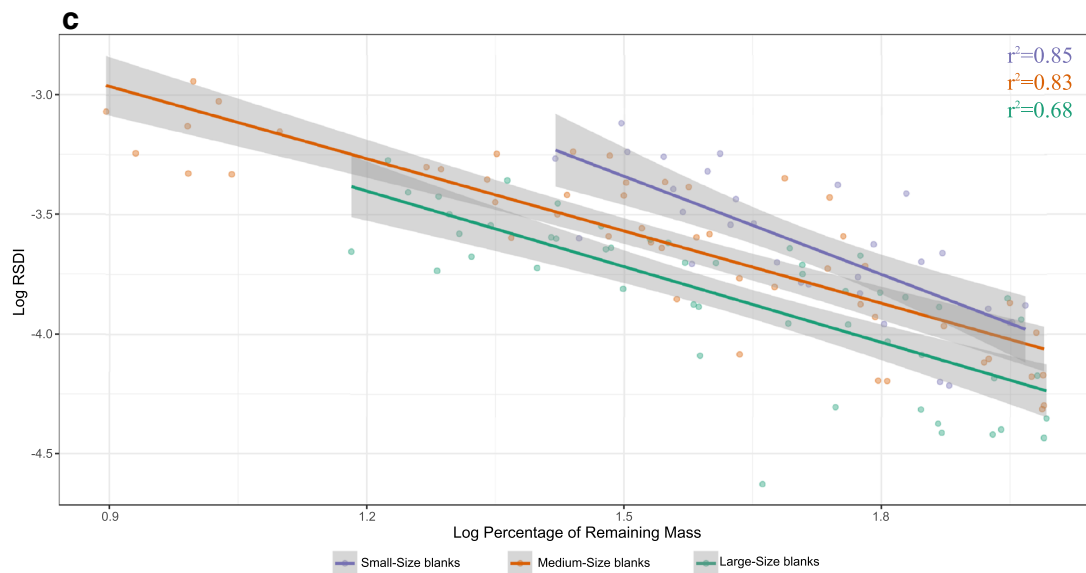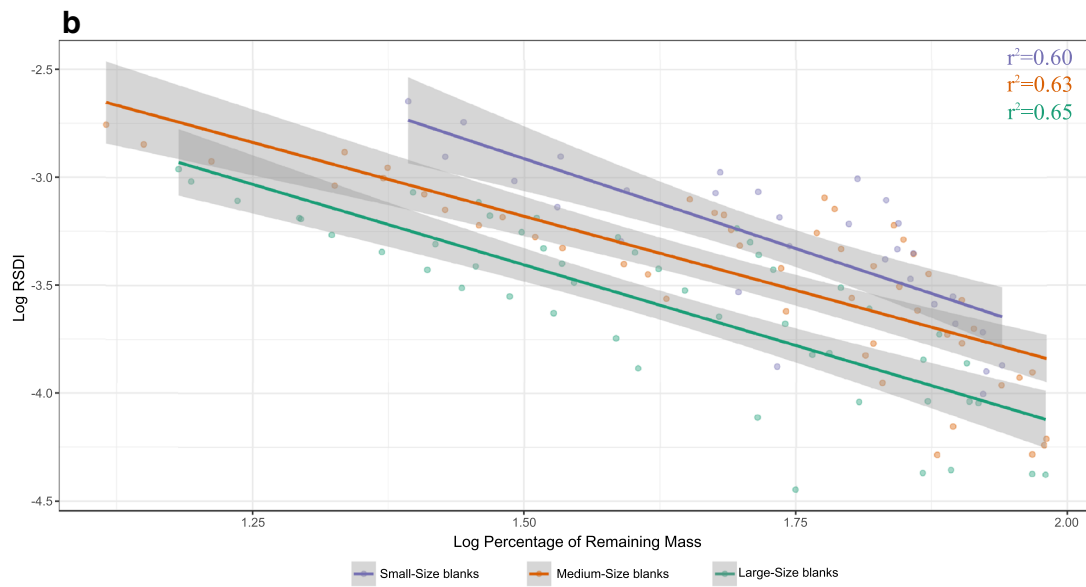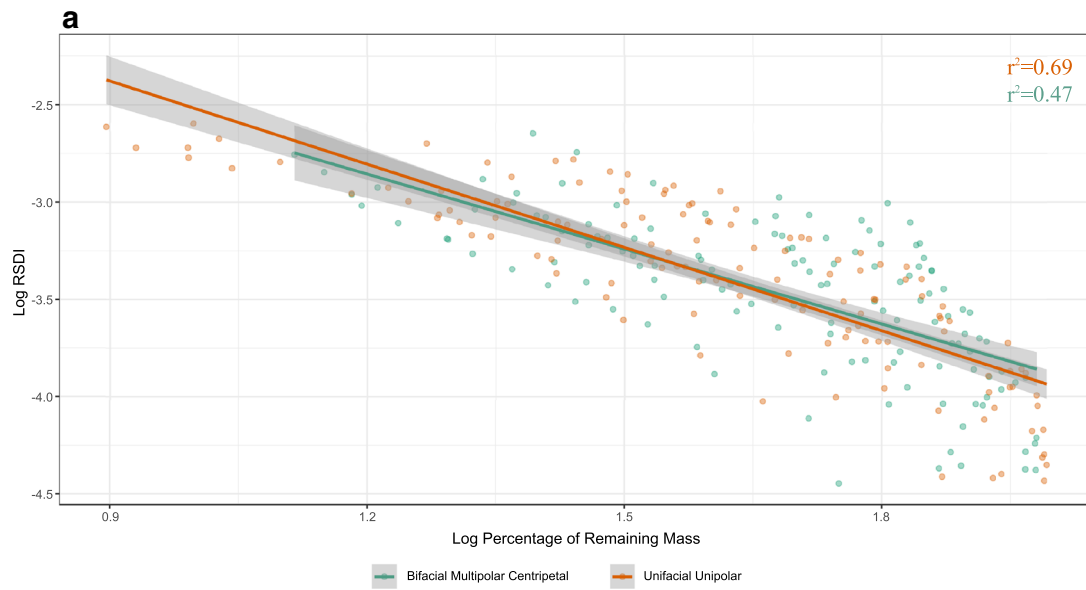
◄ **Fig. 4** Scatter plot showing the relation between log real SDI and log percentage of remaining mass from the core for each of the two core types (**a**), for the three groups of original blank size in BMC cores (**b**), and for the three groups of original blank size in UU cores (**c**)

Regarding the relationship between VSDI and the percentage of remaining mass according to the size of the original blanks, the values of the coefficient of determination for the BMC and UU cores are similar to each other (see Supplementary Material Table S2).

The ANCOVA for the VSDI of the BMC cores provided the same results as the RSDI. In the first model, there was no significant interaction between the size and the percentage of remaining mass ($p = 0.58$), and in the second model, size did significantly affect the visible SDI ($p = 0.00$). ANOVA results indicate that the suppression of the size interaction did not significantly affect the model ($p = 0.58$).

In the case of the VSDI in the UU, the same occurred: suppressing the interaction between the size and percentage of the remaining mass does not affect the performance of the model (ANOVA (p) = 0.37); therefore, the slopes are similar in the three groups of blank sizes.

However, despite not finding statistically significant differences in the slopes of the correlations as a function of the size, we did find differences in the intercepts. At the same reduction stage for both strategies, the cores made on small blanks had higher VSDI values than those made on larger ones.

Percentage of non-cortical surface

Regarding the percentage of non-cortical surface, or FAI, our results show a high correlation between the percentage of non-cortical surface and the percentage of remaining mass, both for the BMC cores ($r^2 = 0.85$), as for the UU cores ($r^2 = 0.83$). However, this correlation dropped considerably when both methods were combined in the same linear model ($r^2 = 0.43$) (see Figs. 6 and 7).

From the percentage of non-cortical surface, we obtain statistically significant differences both in the medians (M-W (p) = 0.00) and in the distribution of the values (K-S (p) = 0.00) between the two reduction strategies (Fig. 8). Therefore, two sets (each from a different reduction strategy) with a similar percentage of remaining mass produce statistically significant differences in both the medians and the distribution of the values. This indicates a different performance of the index throughout the reduction process depending on the type of core reduction strategy.

As in the real and visible SDI, an ANCOVA was used to compare the three regression lines, testing the effect of the original size on the percentage of non-cortical surface while controlling for the effect of the percentage of remaining mass. The first model demonstrated a significant effect on the size and percentage of remaining mass in BMC cores ($p = 0.00$)

but not in UU cores ($p = 0.11$). The interaction between size and percentage of remaining mass was not significant (BMC ($p = 0.26$); UU ($p = 0.09$)). In the second model, size did not significantly affect the percentage of non-cortical surface on UU cores ($p = 0.11$), but it did on the BMC cores ($p = 0.00$). The ANOVA comparing both models indicated that the suppression of size did not affect the model, either for BMC ($p = 0.26$) or for UU ($p = 0.09$).

Discussion and conclusion

Since different reduction indexes have been developed, there is a debate about the universality of its application (Hiscock and Tabrett 2010). Some authors have argued the need for a generalist index that could be applied on different products and tools (i.e., on different types of retouched tools) (Dibble 1995b). In contrast, other authors (Andrefsky 2006, 2009; Clarkson 2002; Eren and Prendergast 2008) argue that a generic index to estimate the intensity of reduction on different retouched artifacts is not possible or adequate and that each specific type of retouched tool requires specific analyses adapted to its characteristics.

In the case of cores, this debate has gone unnoticed at a theoretical level, and on a practical level, research has tended to look for a generalist index that can be applied to all types of core reduction strategies, without considering the specific characteristics of each one. Our results raise certain questions about the proposed methods to estimate a core's reduction intensity, by demonstrating the influence of different reduction strategies and the original size of the nodule on their reliability and accuracy.

First, for both the number of visible scars and the SDI, we were able to verify their appropriate performance in ideal conditions, which is an expression of the rationale behind these approaches. However, our results also allowed us to measure the loss of information due to the advancement in the reduction, through the difference between the actual flake removals and the visible scars. In other words, we can quantify the difference between ideal functioning (RSDI) and functioning in what is the visible archeologically (VSDI). We acknowledge that measuring differences between them in an archeological context is extremely difficult without complementary information from extensive refitting sequences. This study allowed us to identify this degree of measurement error at the experimental level, but it is important to note the necessity of considering the characteristics of the archeological assemblage before applying the SDI to the entire assemblage. In case of application, it is necessary to be aware of this source of error for specific knapping methods, such as the reduction underestimation in unifacial ones.

In relation to the number of scars, as the reduction progresses, an overlapping effect is produced whereby the new
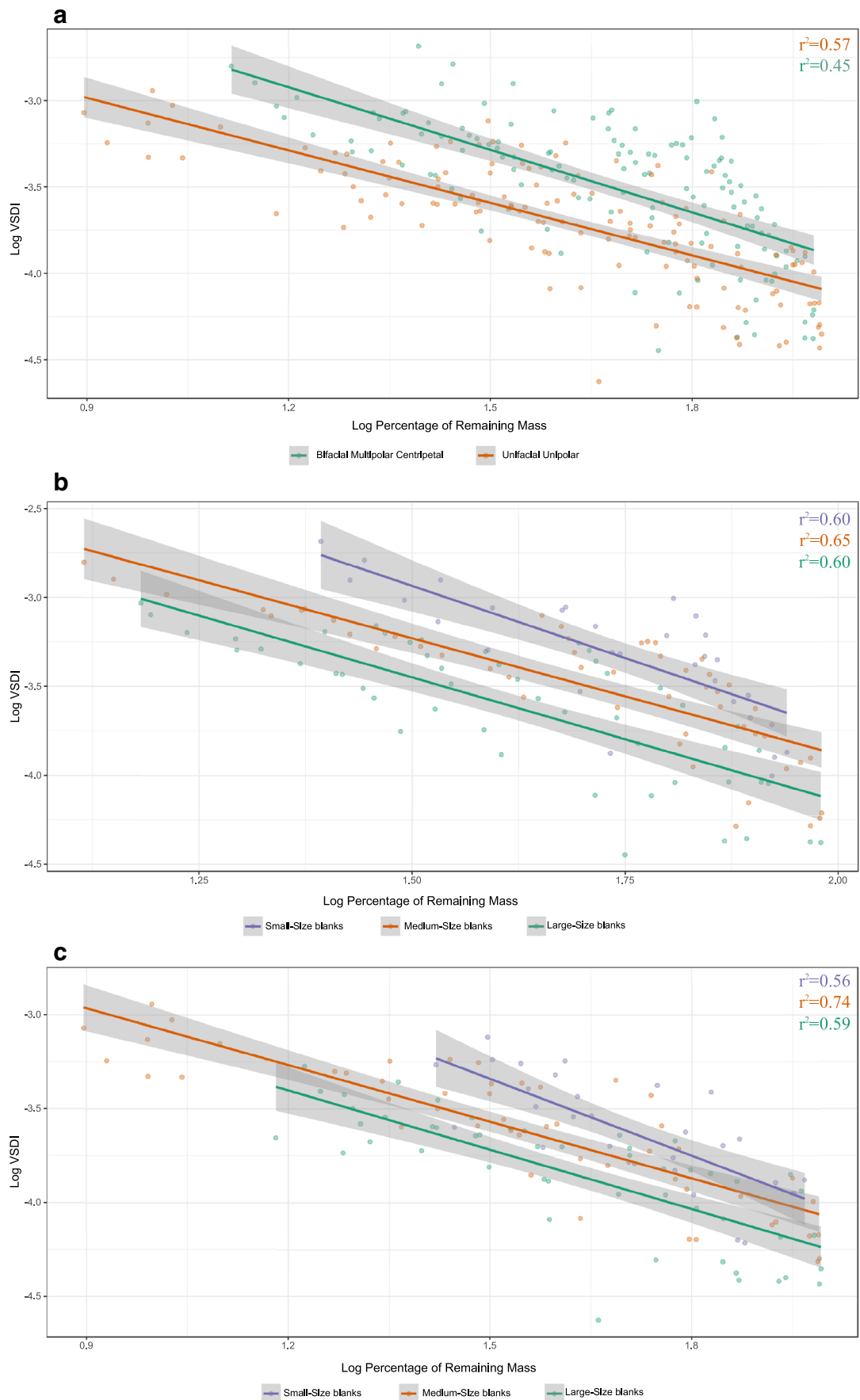
◀ **Fig. 5** Scatter plot showing the relation between log visible SDI and log percentage of remaining mass from the core for each of the two core types (**a**), for the three groups of original blank size in BMC cores (**b**), and for the three groups of original blank size in UU cores (**c**)

detachments remove the scars of previous extractions from the core surface. This process occurs at a different pace in bifacial multipolar centripetal and unifacial unipolar strategies, with the latter being affected more, especially in cases where the exploitation is concentrated on a specific area of the blank. The size of the blanks does not influence the scars' overlapping effect on both reduction strategies in the same way, since (1) in the unifacial unipolar strategy, there is a greater superposition of scars in the smaller blanks, possibly due to the fact that in large-sized cores, shorter and/or hinged flakes that are not as deep in the exploitation surface as in previous generations can be more frequent and (2) in the bifacial multipolar centripetal strategy, the size does not affect the probability that more or fewer scar overlaps occur.

In the case of the non-cortical surface, something similar happens, as it has a very high coefficient of determination when each core reduction strategy is analyzed independently. However, this value decreases considerably if applied to different core reduction strategies together. This is because cortical surface is removed at a different rate depending on the reduction strategy. In this way, in the unifacial unipolar cores, the elimination of the entire cortical surface will never occur. On the other hand, the removal of the cortical surface tends to occur very quickly, in bifacial multipolar centripetal reduction strategy.

This also has implications for other parameters, such as the amount of cortical surface or the number of scars present on the dorsal surface of the flakes, which have been used as indicators of reduction on assemblages from a general perspective (Cowan 1999; Marwick 2008; Odell 1989). In this way, it has been interpreted that the more intense the reduction is, the higher the proportion of non-cortical flakes in an assemblage (Dibble et al. 2005), since the flakes with a high percentage of cortex come from the early stages of nodule reduction, and that the dorsal surfaces will present more scars as reduction advances. It is true that core morphology seems to have less influence than other parameters (such as exterior platform angle and platform depth) on the size and shape of the obtained flakes (Rezek et al. 2011). However, as we have seen, the differential effect of the scars' overlapping according to the core reduction strategy can influence the dorsal cortical surface and the number of scars present on the dorsal surface of the flakes, thereby producing flakes without cortical surface or with several scars on their dorsal surfaces from very early moments of the reduction and vice versa.

Some of these parameters (e.g., percentage of non-cortical surface, SDI) allow diachronic and synchronic comparisons of the intensities of reduction on the same type of reduction strategies. However, our results suggest that it is not adequate/accurate to compare the reduction intensity on different core reduction strategies. In doing so, one runs the risk of underestimating the results of those exploitation strategies that affect a sector of the core in a more recurrent way (i.e., Quina core reduction strategy), with respect to those that present a greater perimetric development along the edge of the core (e.g., discoid core reduction strategy).

Other variables that have been used as an indicator of reduction are the number of exploitation surfaces and the number of convergences between exploitation surfaces (Douglass et al. 2017). However, these do not seem to be parameters that work regardless of the type of reduction strategy, since as the reduction progresses, the number of exploitation surfaces does not always increase. In our experiment, we have discarded this variable since we have dealt with two specific types of core reduction strategies.

The number of removals made on each core—that is, the ratio of flakes per core—is a variable with a relatively high coefficient of determination independent of the type of reduction strategy. However, it is an index that can only be treated at an overall level, since it is not easy to relate flakes and reduction strategies, especially for flakes from the early stages of reduction, without the refitting of technical sequences. Although it can be a useful proxy and would allow comparisons between different raw materials, for example, it does not allow for the study of internal differences that may exist in the intensity of reduction between strategies and knapping methods within the same archeological assemblage. Moreover, it is necessary to bear in mind questions like the integrity of the assemblage or economic behaviors like blank transport or spatial variation on discard patterns that could significantly affect the count of flakes on an archeological assemblage.

Conversely, the mass of the discarded core has a very low coefficient of determination, since the size of the original blanks in this experiment is highly variable, and therefore, smaller cores are not always the most reduced ones. Therefore, the final mass of the cores does not seem to be a very reliable proxy when estimating the reduction on cores if the original blanks used are not well known.

Furthermore, the size of the original blanks affects not only the final mass of the cores, but also other variables. This is the case of the scar density index, which, as Ditchfield (2016) pointed out, grows to a greater extent with respect to an increase in reduction in the small-sized cores than in the larger ones. However, in that experiment, reduction stages were used instead of the percentage of remaining or extracted mass. The use of reduction stages is problematic, since they do not represent a real entity (Bradbury and Carr 1999; Shott 2017; Shott et al. 2011), and therefore, within a single stage. there can be a great deal of internal variability with respect to the percentage of mass extracted from the core. In addition, the

values obtained through the reduction estimation methods are aimed at estimating the amount of mass removed, and not the sequence of morphological changes (Hiscock and Tabrett 2010). Therefore, when evaluating the inferential capacity of the reduction estimation methods through experimental studies, it is more appropriate to directly use the percentage of remaining mass as an objective and real reduction reference.

Shipton and Clarkson (2015a) verified how the SDI evolves differently in the reduction of handaxes, depending on the type of blank on which they are made. This difference has been attributed to the extraction of fewer (and larger) flakes on the handaxes made on cobbles or nodules and of more (and smaller) flakes on the handaxes made on flakes. The results of our experiment suggest that, at the same moment of reduction, the value of the SDI is higher on the cores made on smaller blanks. Although SDI works proportionally in all sizes as the reduction progresses, it varies based on the original size and morphology, resulting in an overestimation of the reduction on the smaller cores with respect to the larger ones.

At the archeological level, it is not difficult to think of scenarios in which these problems can affect the results obtained. For example, in a case where there are cores on flakes and cores on cobbles or nodules, with great heterogeneity in the size of the blanks, we would obtain lower values of reduction for the cores on cobbles or nodules with respect to those on flake; within cobbles or nodules, the reduction of the larger ones may be underestimated with respect to those smaller in size.

Taking this into consideration, we think that it is necessary to consider a series of aspects in order to more accurately analyze the intensity of reduction on cores:

- Faciality of exploitation: the less surface of a blank is exploited, the more likely it is that exploitation is more recurrent, so—although it is not strictly necessary—one would expect a unifacial core to tend to be more susceptible to the overlapping of scars and to lose cortical surface at a lower rate than a bifacial or multifacial core.

- Perimetric development of the reduction: the less the perimeter of a blank is exploited, the more likely it is that (1) the scars will overlap as the reduction progresses and (2) the less cortical surface will be eliminated. Conversely, in reduction strategies with a wider perimetric development, (1) the elimination of previous scars by the removal of new flakes will be less common (or will happen at a later stage of the reduction) and (2) the removal of cortical surface will be more extensive.
- The size of the original blank: it would be necessary to look for parameters that work in a similar way for different sizes of the original blanks, or at least to take into account the size of the blanks when performing reduction intensity analyses, especially in those cases in which the methods/proxies depend directly or partially on the dimensions of

Fig. 6 Scatter plot showing the relation between percentage of non-cortical surface and percentage of remaining mass from the core for each of the two core types (**a**), for the three groups of original blank size in BMC cores (**b**), and for the three groups of original blank size in UU cores (**c**) ▶

the cores (such as the scar density index, through the surface). Therefore, the size can markedly affect the reliability of the estimations.

The methods/proxies proposed in the literature are useful and informative as long as these aforementioned aspects are adequately contextualized (types and formats of raw material blanks, types of reduction strategies, degree of recurrence in the exploitation sequence, etc.). The main concern of not finding one or more parameters that respond adequately to the intensity of reduction on different reduction strategies, but the difficulty to make comparisons without falling into the overestimation or underestimation of some specific types of cores and thus leading to a misinterpretation of the degree of reduction in an archeological assemblage.

Using different methods to cross-check the data obtained, as suggested by Dibble (1995b), would be a meticulous strategy that would provide accuracy and reliability to the inferences drawn. Adapting the reduction analysis according to the specific characteristics of the reduction strategies (by applying the most suitable method to each reduction strategy) can be another good option to statistically compare the degree of reduction in the same reduction strategies among different archeological assemblages. However, studying each type of core reduction based on specific parameters and different from one another precludes direct statistical comparison between reduction strategies, given that each method establishes independent scales. Therefore, although inter-assemblage reduction intensity could be statistically compared when dealing with similar reduction strategies, comparisons between different ones in the same assemblage should be limited to the qualitative sphere at the moment, by contrasting the specific inferences of each method for the reduction intensity of every type of core reduction strategy.

The fact that there is currently no method of "universal" application to infer the intensity of reduction on cores, regardless of the types of reduction strategies and the initial size of the blanks, does not mean that these kinds of studies should be abandoned. New methods for the study of the reduction intensity on different types of production strategies aiming to minimize the overrrepresentation or underrepresentation of the results obtained should be explored.

Besides, these new approaches should aim to establish a common measurement unit, in order to allow statistical comparisons between the specific reduction analyses. In this way, measuring reduction intensity as percentage of remaining/extracted mass should be the goal for many reasons. First, because being a

a

b

c
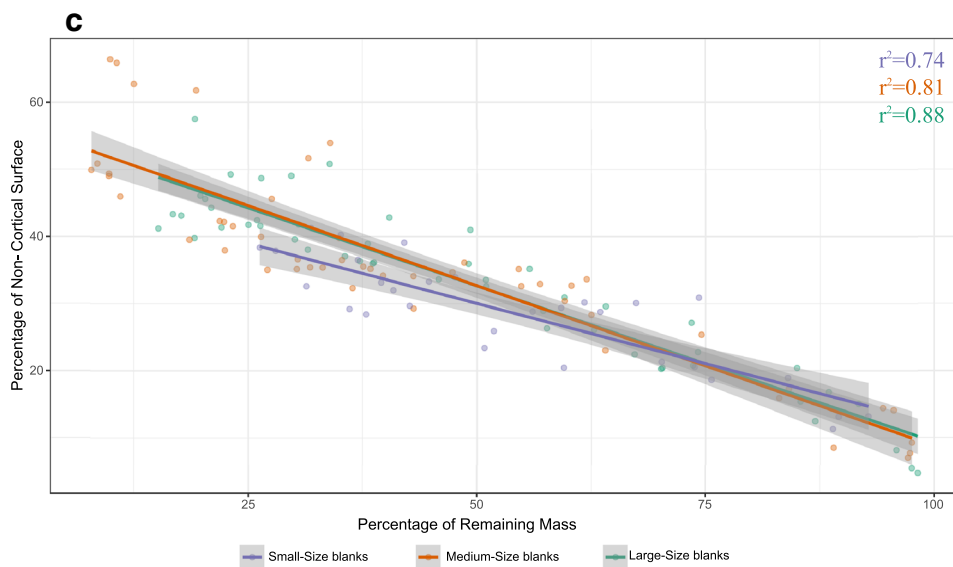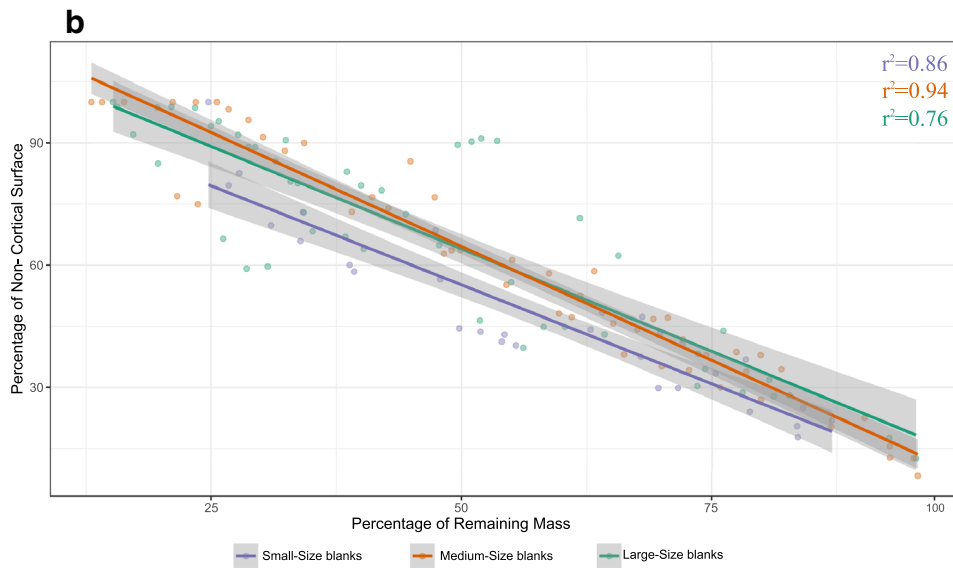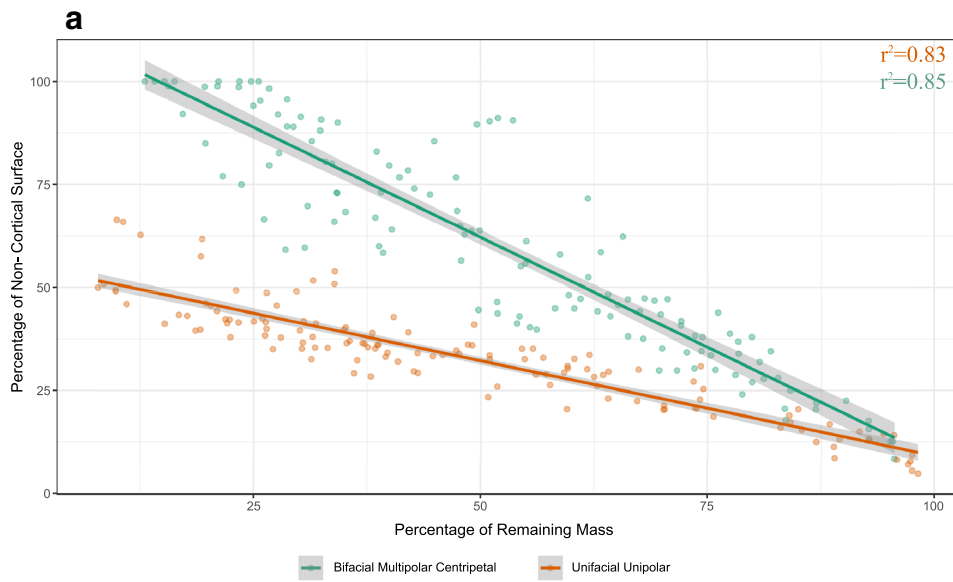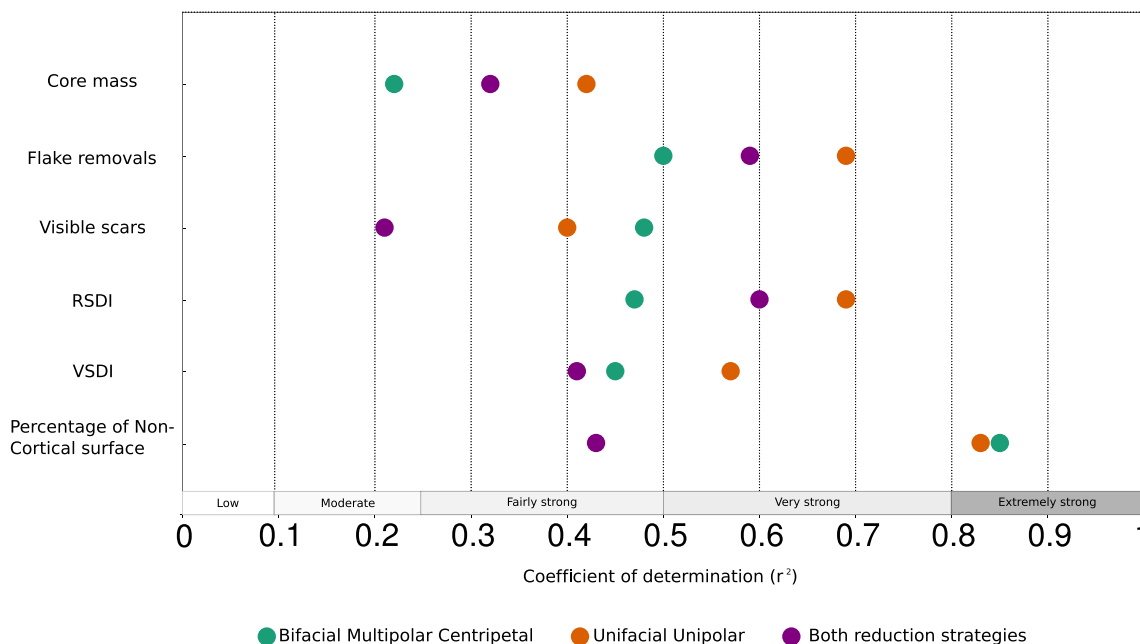
Fig. 7 Scatter plot showing the coefficient of determination results (r^2) between different variables and percentage of mass remaining from the core. The gray scale indicates the power of inference according to Hiscock and Tabrett (2010)
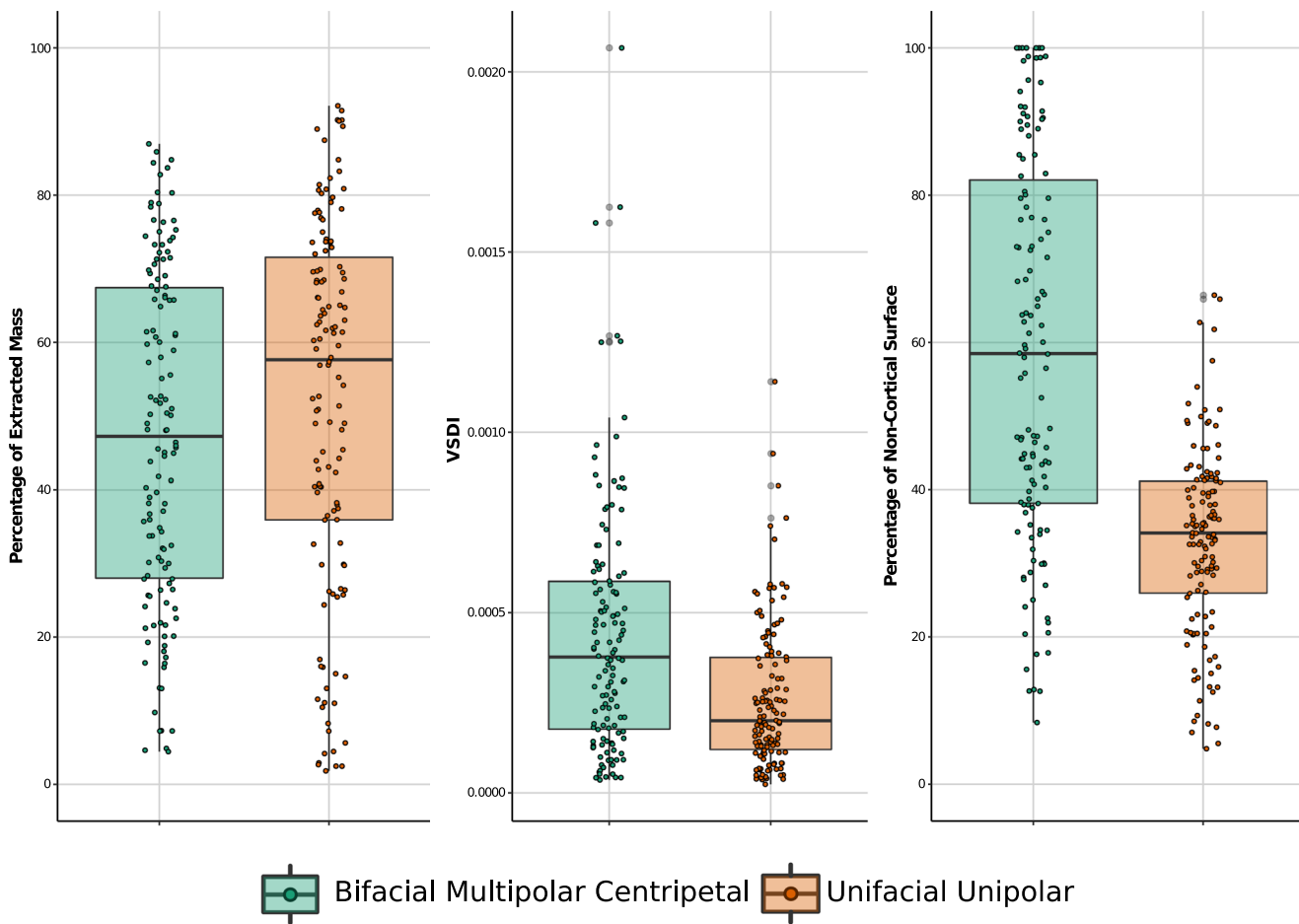
Fig. 8 Box and jitter plot of percentage of remaining mass for core for both core types (left), visible SDI (middle), and percentage of non-cortical surface (right)

real and tangible measurement, on a 0 to 100 scale, and not the product of an index with no stablished scale limits, it allows to study the reduction intensity of a single assemblage without any comparative sample. Moreover, the intra- and inter-assemblage comparisons would be more accurate, allowing the qualitative assessment of the quantitative results.

With this in mind, two topics appear as future research lines: (1) the characterization of the size or format of the initial blanks, or at least the exploration of tools that allow the estimation of the reduction while preventing distortions created by the size factor, and (2) the development of a way to study the recurrent exploitations, in which greater reduction implies greater loss of information and therefore more difficult to reliably estimate reduction intensity. At the technological level, there are other examples in which the loss of information seems irreparable. This is the case in retouched tools, such as endscrapers (Eren et al. 2005; Kuhn 1990; Morales et al. 2013), in which the distal edge is retouched in a similar way to how an unifacial unipolar core is exploited, and for which there are numerous methodological proposals for the quantification of the extracted mass. We have verified with our results that there is currently no method or parameter completely independent of the size and core reduction strategies by which to study the degree of reduction in a complete assemblage of cores. However, we propose some ideas to mitigate those concerns and encourage researchers to continue exploring new indexes and parameters that could work on different types of reduction strategies and blanks, and to continue improving the current ones.

Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

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