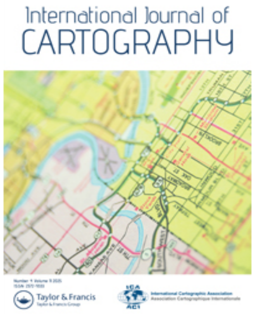

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Concept or adaptive spatial unit scaling in multi-temporal thematic maps for representing change

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ABSTRACT

The increasing demand for and availability of multi-temporal data is also leading to the growing importance of usable multi-temporal thematic maps. However, the respective conventional map types have a number of disadvantages, both for animated and static visualisation. The innovative approach of this research is to test an alternative graphical coding by adjusting the size of spatial (or enumeration) units according to the change of values (instead of using lightness/saturation or graduated symbols). This idea is based on the concept of Value by Area Maps, which has so far only been used almost exclusively for mono-temporal maps.

The aim of this work is to develop a concept for an adaptive scaling of spatial units for the visualisation of changes. This includes the consideration of different, flexible scaling functions (proportional, exponential, range-graded) to highlight specific changes, the distinction between *Total Change Maps* (i.e. the total map size is changed according to the total value change) and *Normalised Change Maps* (i.e. the total map size is kept constant over all epochs of time) and the integration of original value data by dual coding (including an a priori data classification that preserves changes).

This concept is demonstrated and discussed using a real data set. In addition, the results of a small, preliminary qualitative study are presented that confirm the general applicability of this concept and point to the necessity of further developments and future empirical studies.

RÉSUMÉ

La demande et la disponibilité croissante de données multi-temporelles induisent également l'importance grandissante des cartes thématiques multi-temporelles utilisables. Pourtant les types de cartes conventionnelles, à visualisation statique ou dynamique, ont l'un comme l'autre un certain nombre de désavantages. L'approche innovante de cette recherche est de tester un codage graphique alternatif en ajustant la taille des unités spatiales (ou les dénombrements) en fonction des changements de valeurs (au lieu d'utiliser les variables de luminosité/saturation ou les symboles gradués). Cette idée est basée sur le concept de carte de valeur par zone, ou

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cartogramme, qui a jusqu'à présent été utilisé, quasiment exclusivement, pour des cartes mono-temporelles.

Le but de ce travail est de développer un concept pour une mise à l'échelle adaptative des unités spatiales pour la visualisation des changements. Cela inclut la prise en compte de fonctions d'échelle flexibles (proportionnelles, exponentielles, graduées) pour mettre en valeur des changements spécifiques, la différentiation entre les cartes de changement total (i.e. la taille totale de la carte est changée en fonction de la valeur totale du changement) et les cartes à changement normalisé (i.e. la taille totale de la carte reste constante pour toutes les époques), et l'intégration de données de valeurs initiales pour un codage dual (y compris une classification de données prédéfinie qui préserve les changements).

Ce concept est présenté et discuté avec des données réelles. En plus, les résultats d'une petite étude qualitative préliminaire sont présentés. Ils confirment l'applicabilité générale de notre concept et soulignent la nécessité de développements supplémentaires et de futures études empiriques

1. Introduction

1.1. Relevance and focus

Goal of this paper is to introduce an innovative concept that, generally speaking, aims at the improvement of the usability of multi-temporal maps. The relevance of this topic results from the increased demand and availability of multi-temporal geodata. On the one hand, the demand is increasing due to current and time-critical applications – such as epidemiology, climate and environmental change, energy supply, disaster management, weather forecasting, transport, mobility, tourism, e-commerce, oceanography and others. On the other hand, the availability and distribution of large multi-temporal data sets is generally no longer a problem due to technological developments – caused by satellite, drone or terrestrial-based sensors, sensor networks or simply the availability of GNSS in smartphones, which lead to intensive user-generated data collection (Bill et al., 2022).

This demand and availability also increase the need for powerful geo analytics. Methods of artificial intelligence and machine/deep learning are currently being promoted as promising solutions (Scheider & Richter, 2023) and have already led to initial successes also in cartographic applications such as building generalization (e.g. Touya et al., 2019; Sester, 2020). However, due to heterogeneous and qualitatively diverse training and test data, Cartography represents a difficult use case, especially in the context of map design (Tao & Xu, 2023). Consequently, advanced computational methods and the integration of human knowledge should definitely be further developed (*human-in-the-loop*; Meng, 2020; Roussel & Böhm, 2023). In other words, following the demand for more powerful geo analytics, there is an increased need for effective and efficient cartographic visualization of multi-temporal data in the future – including the task of detecting and analysing changes in the data (Cybulski, 2022).

When such multi-temporal datasets consist of quantitative and area-based data, a series of symbol or choropleth maps are a very commonly used visualization type, especially in the media (Mooney & Juhász, 2020). These are usually presented as cartographic animations or map series (here, especially as small multiples; DiBiase et al., 1992; Slocum et al., 2009). Although animations in particular have clear disadvantages in terms of perceptibility (Rensink, 2002), added value has been demonstrated in the communication of spatio-temporal trends (Harrower & Fabrikant, 2008), processes and patterns (Lan et al., 2021), or clusters (Griffin et al., 2006).

1.2. Problem setting

Multi-temporal data poses a particular challenge for thematic mapping, as the numerous epochs mean that there is an extended volume of data and perceptual limitations in terms of viewing duration (for animations; Harrower, 2007; Rensink, 2002) or limited space or legibility (for small multiples).

Depending on the map type, values are often coded by symbol sizes and colour lightness (or saturation). The actual changes (such as the size of change or trends) have to be processed mentally by the user: while the comparison of single symbol sizes for raw totals is relatively straightforward, the comparison of lightness values (in particular, by considering the 'dark is more-bias', Robinson et al., 1984) is a little bit more difficult. When it comes to the task of discovering overall (important) trends and patterns in the whole map series, however, there is even an extended mental transfer necessary.

1.3. General approach

The idea of this research is to test an alternative change coding in multi-temporal maps by adjusting the size of spatial units according to the change of values. An example for this straightforward concept: doubling the area size of an enumeration unit between two epochs corresponds to double value size. This principle is well known from graduated symbol maps where the size of symbols is adjusted according to quantitative values. The transfer from symbol size to spatial unit size leads to the concept of Value by Area-Maps (Dorling et al., 2006). However, this was used almost exclusively for single and static maps and a consideration of the total map size did not take place, as input and output maps are generally of the same size.

It is hypothesized that the change coding is easier to comprehend (in particular, against lightness coding) because it does not need any legend (at least for qualitative tasks) and is also capable of showing total trends. Furthermore, it is also of advantage that there is a clear and direct connection between the coding and the areas of interest.

It is of course predictable that a quantitative evaluation is more difficult due to changing sizes of very irregular spatial units (in particular, of administrative units). For such a case, it is possible to apply a dual coding approach – for example, by adding a colour lightness coding to represent the original values.

1.4. Goals and outline of paper

The overall goal of this paper is to present the concept for spatial unit scaling for representing changes in multi-temporal maps. This includes various options concerning

- the application of different scaling functions (proportional, exponential, range-graded) in order to be able to emphasize certain changes,
- the use of *Total Change Maps* (i.e. total map size is changed according to total value change) versus *Normalized Change Maps* (i.e. total map size is kept constant over all epochs of time), and
- the integration of original value data by dual coding (including an a priori data classification that preserves changes).

The remainder of this paper is structured as follows: after a literature review (Section 2), the overall concept is described in Section 3. The actual application to a real, multi-temporal data set (consisting of five epochs) is presented in Section 4. An in-depth quantitative testing is not within the scope of this paper; however, a small, qualitative survey is undertaken that gives some insights about the general feasibility of the concept (Section 5). All findings are discussed in Section 6, leading to the summary and conclusions in Section 7.

2. Previous work

2.1. Coding changes in multi-temporal maps

Focusing on the graphical design for multi-temporal (in particular, choropleth) maps, topics such as integration of interactive elements (Harrower & Fabrikant, 2008), placing legends (Kraak et al., 1997), usage of speech or sound (Muehlenhaus, 2013), or interpolation between map frames (Fish et al., 2011) are treated. Relatively few studies have concentrated on different graphical variables, with colour (i.e. hue, lightness, saturation) being the variable that has been studied most frequently (e.g. Fish et al., 2011; Moon et al., 2014; Traun et al., 2021).

Considering size as graphical variable to depict changes, Kostelnick et al. (2007) empirically examined the magnitude of size change, display method, and number of items in the displays with respect to graduated circle symbols. Among others, they found that there were biases towards more bigger judgements when large size changes occur or when animated changes were presented.

The comparison and also the simultaneous coding of the variables colour and size – the latter as the size of symbols – yielded different results: while Kronenfeld and Yoo (2023) found no added value of symbol sizes compared to colour in choropleth maps, Cybulski and Medyńska-Gulij (2018) recognized an improved detection of extreme values through the redundant representation, even if the effect of change blindness could not be completely eliminated.

2.2. Use of value by area maps

The underlying idea of this paper is not to use symbol sizes (such as graduated circles), instead, it is to change the size of entire spatial units according to value changes. This leads to the concept of Value by Area Maps (VbAMs), which scale the enumeration units not in relation to the real geographic area size, but to an attribute value (Dent, 1975). This type of map belongs to the class of contiguous cartograms, in which the shape of the spatial units is distorted, but the topology of all direct neighborhoods is preserved. The original method for computer-aided generation was described by Dorling (1996). Gastner and Newman (2004) presented a diffusion method that allowed a faster computation. Gastner et al. (2018) published a further development based on a continuous transformation, which will be used in the further course of this project. Nusrat and Kobourov (2016) in their work on various types of cartograms also covered variations of Value by Area Maps.

VbAMs are often considered unusual and attractive (Parlapiano, 2016), but also exhibit distortions or even losses of positional fidelity and pattern preservation (Kronenfeld & Yoo, 2023). These properties are also reflected in some studies concerning the usability of VbAMs for representing quantitative data. For example, Dent (1975) and Griffin (1983) recommended the combination with a Ground Plane Alike-Map (e.g. as an insert map) and the use of a legend. Duncan et al. (2021) suggest interactive elements if VbAMs are displayed electronically. Kaspar et al. (2011) compared the usage of VbAMs with choropleth maps, which are enriched by graduated circles: in general, the latter type yielded more effective and efficient usage. However, satisfying results were also obtained with the VbAMs alternative – depending on the task complexity and on the shapes of enumeration units.

Developments to avoid the shape distortion effects of VbAMs led to a compromise solution between choropleth maps and VbAMs – the so-called *Sponge Maps* (Schiewe, 2023a). Here, different adapted scaling factors are introduced in order to adjust the reference area sizes for specific needs. The idea is to distort the reference map only to such an extent that the shapes and relations are still recognizable, but 'important' small areas are emphasized more strongly.

All in all, it can be stated that a transfer and the proof of the concept of Value by Area Maps (as well as the one of Sponge Maps) to multi-temporal display – and the task of change detection – has not yet taken place in sufficient depth.

3. Concept

3.1. General approach

The overall idea is to encode value changes through changes in the sizes of spatial units (typically, enumeration units) by adapting the idea of Value by Area-maps. By doing so, either differences or quotients of quantitative changes can be considered. In the following, we focus on quotients, as this makes perception and interpretation easier. For example, a value twice as large between two epochs of time can lead to an area twice as large.

Any scaling might lead to huge map size differences for the total map or to undesirable strong distortions of individual regions with a decrease in legibility (e.g. for the recognition of certain states). This is the reason to provide different scaling functions.

By transforming value changes into graphical sizes, either a regular scaling is performed (Total Change Maps, TCM; i.e. scaling the individual regions also leads to a scaling of the total map size), or an area normalization takes place (Normalized Change Maps, NCM; i.e. the total map size of the first epoch is kept for all epochs). With the NCM option the size of areal units does not directly reflect change quotients anymore, but the change in comparison to other regions (Section 3.3).

Strictly speaking, only those data should be used for scaling spatial units that change only at unit boundaries – such as area-based (also: relative or standardized) data for producing choropleth maps. However, as symbol size is the typical display option for raw-total (absolute) data, it seems to be intuitive to apply area-based scaling also to the latter data type. Certainly, this relaxation of strict cartographical principles has to be empirically investigated later.

3.2. Scaling functions

The general scaling principle can be reduced to a bi-temporal event (i.e. having epochs t_i and t_{i-1}) for each spatial unit. A concatenation of such bi-temporal events for all units describes the entire multi-temporal map scenario. Given are absolute values v_i for respective time epochs as well as the area size A_1 of the very first map in the series that represents a Ground Plane Alike Map.

The proportional scaling for individual spatial units calculates the new area A_i by considering the change quotient Q_i of values v_i and v_1 as follows:

$$Q_i = \frac{v_i}{v_1} \tag{1}$$

$$A_i = c\, Q_i\, A_1 = Q_i^{'}\, A_1 \tag{2}$$

In principle, proportional scaling is rather simple to understand: all ratios (of single enumeration units, as well as of the entire area) are shown in a proportional manner. For $c = 1$ the quotient between value and size change is even identical. Because the sum of area sizes A_i for all enumeration units typically differ from epoch to epoch, also the overall size of the map is changed (i.e. enlarged or reduced). Figure 1 (top row) demonstrates the principle for two different factors ($c = 1$, $c = 2$). The setting of $c > 1$ can be used to magnify the change impression.

Using v_1 and A_1 in the denominator of the above formulas instead of v_{i-1} and A_{i-1} follows the reason that the latter setting with $c \neq 1$ could lead to undesired area proportions between epochs that are larger than one lag apart from each other. For example, representing the original values [$v_1 = 10$, $v_2 = 20$, $v_3 = 10$] with the epoch-by-epoch procedure (v_{i-1}, A_{i-1}) with $c = 3$ would lead to area changes [$Q_1' = 10$, $Q_2' = 10 \cdot 2 \cdot 3 = 60$, $Q_3' = 60 \cdot 0.5 \cdot 3 = 90$] – although one expects that the last value Q_3' should be smaller than the second and identical to the first value. In addition, this definition of change allows to modify the time scale (or just to remove certain epochs) without the need for re-calculation so that important changes can be highlighted.

An exponential function in a simple form applies the exponent r to the change quotient:

$$Q'_i = (Q_i)^r = \left(\frac{v_i}{v_1}\right)^r \tag{3}$$

Figure 1 (bottom left) demonstrates the potential emphasizing effect of exponential scaling. Furthermore, change quotients can also grouped into classes (range graded scaling; Figure 1, bottom right) and assigned with specific factors Q_i'. As with the common data classification, differences are thus visually emphasised – at the

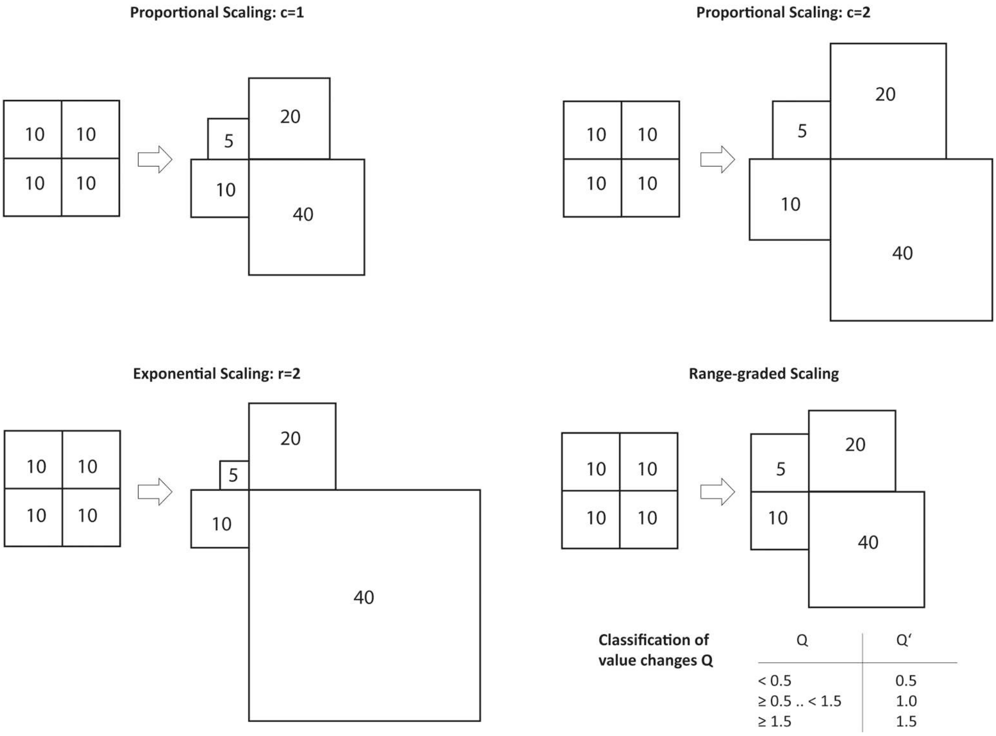

Figure 1. Different scaling functions in a schematic manner (please note: labels inside single regions only serve for explanation purposes).

expense of the exact proportions – but fewer mental resources are used for interpretation purposes. As the example in Figure 1 shows, rather small changes (with $0.5 \leq Qi < 1{,}5$) are not scaled at all – with the effect, that all other changes appear more prominently.

3.3. Total change maps vs. normalized change maps

Previously, it was assumed that the size of the total map grows in line with the scaling of the individual regions (Total Change Maps, TCM). Alternatively, it can also be defined that the overall size of map is kept the same for all epochs of time (Normalized Change Maps, NCM). Given the actual area sizes A_i, the normalization to area sizes A_i' takes place through (with u describing all spatial units)

$$A'_i = A_i \frac{\sum_u A_1}{\sum_u A_i} \tag{4}$$

The normalized representation does not inherit the possible space problems of TCMs anymore (Figure 2). However, it does not represent absolute change ratios but change ratios in comparison to all other change ratios in the map (in other words, the distribution of changes). This might be difficult to understand or is at least not intuitive for many map readers.

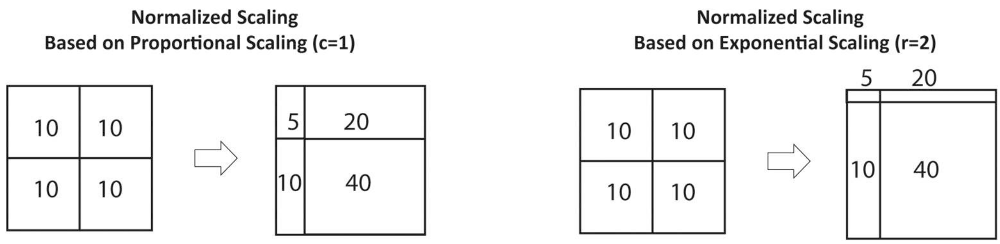

Figure 2. Two options of normalized scaling with different scaling functions (please note: labels inside single regions only serve for explanation purposes).

3.4. Dual coding

For reasons of simplification, the previous examples were based on identically sized spatial units for t = 1. This is of course not the normal case. Figure 3 (top) shows an example, in which regions of the same size (A and B) have different values v after scaling. On the one hand, this can lead to confusion (which must be clarified in empirical studies) and, on the other hand, to a loss of information about the values v as such.

In order to integrate the actual values, well-known cartographical coding methods can be applied in addition (e.g. labels, graduated symbols for raw-totals or colour lightness for area-based data). Of course, such a dual coding might lead to mental overload, if not confusion with users. Empirical tests are needed to investigate this problem in detail.

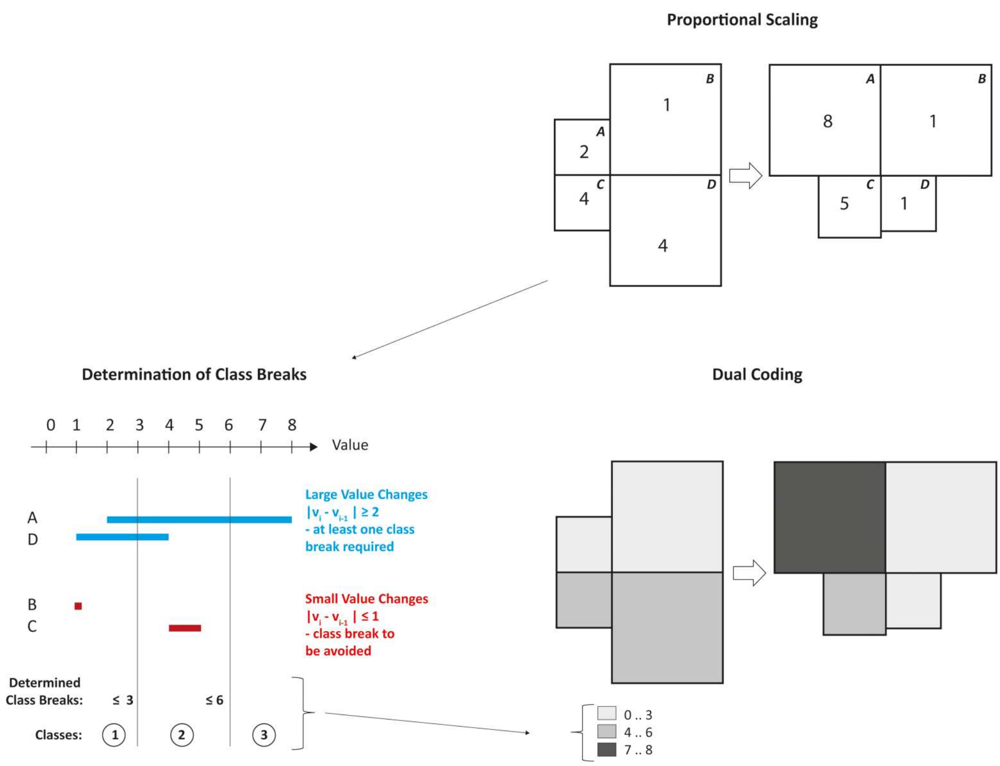

Figure 3. Proportional scaling (top) with different initial spatial unit sizes; corresponding determination of class breaks and dual coding (bottom).

In the case of additionally using conventional colour lightness coding, a classification of original values v (not to confuse with the classification of change quotients as for range-graded scaling; Section 3.2) and an attachment of respective colour lightness values to spatial units can be applied. For this purpose, any general data classification method can be used. However, the conventional methods (such as equidistant or quantiles) do not consider the preservation of 'important' change information as they are placing the class limits based on a data or histogram driven base only. Schiewe (2023b) presented a method that explicitly defines and preserves 'important' changes to a certain extent. In a simplified manner, one can require the following – after setting a priori the desired number of classes and respective thresholds Δ_{LARGE} and Δ_{SMALL}:

- introduce at least one class break for large value differences $| v_i - v_{i-1} | \geq \Delta_{LARGE}$
- avoid class breaks for small value differences $| v_i - v_{i-1} | \leq \Delta_{SMALL}$

Figure 3 (bottom left) shows an example for determining the class boundaries. In this case, the solution is obvious and all conditions can be simply met. However, a larger number of value differences $| v_i - v_{i-1} |$ may lead to the fact that not all conditions can be fulfilled. In such a case, a sweep line algorithm is used that pushes a line across the intervals and counts the number of fulfilled conditions (i.e. the intersection with desired intervals and the non-intersection with undesired intervals) at each stop. These sweep line stops are defined at each start and end of a value interval. Since several classes are to be created, all combinations of intersection lines are then compiled in a brute force procedure, the maximum total number of fulfilled conditions then gives the final result for the set of class break lines.

This data classification can easily be extended to the multi-temporal case, in which all differences $| v_i - v_{i-1} |$ for all epochs are included in the analysis. In addition to this elementary procedure, different weights can be assigned to specific differences $| v_i - v_{i-1} |$ – for example, to increase the probability of preserving particularly large differences.

3.5. Map design issues

Applying any scaling function yields an area change $Q_i' = A_i / A_1$ for each spatial unit. This change is typically represented in two graphical dimensions – for example for $Q_i' = 2$ this results in an increase by factors $\sqrt{2}$ in both height and width. However, it is well known that people find it difficult to estimate proportions from areal shapes – a fact that led to perceptual scaling as an alternative to strict mathematical scaling. The most prominent perceptual scaling approach is the Flannery adjustment (Flannery, 1971), which can be applied to circular symbols. As we work with heterogeneous and irregular shapes in this spatial unit scaling approach, this compensation is strictly speaking not applicable. It is future work to find compromise solutions for perceptual scaling in this context, if necessary at all.

One weakness of spatial unit size changes is the impossible, exact determination of the associated values. Nevertheless, an explanation of size changes is also necessary for qualitative evaluation purposes. In contrast to the representation of symbol sizes in legends, a problem arises with the maps shown here: using an adjacent legend that displays possible overall sizes of single regions or even the total maps, requires too much space. Exemplary,

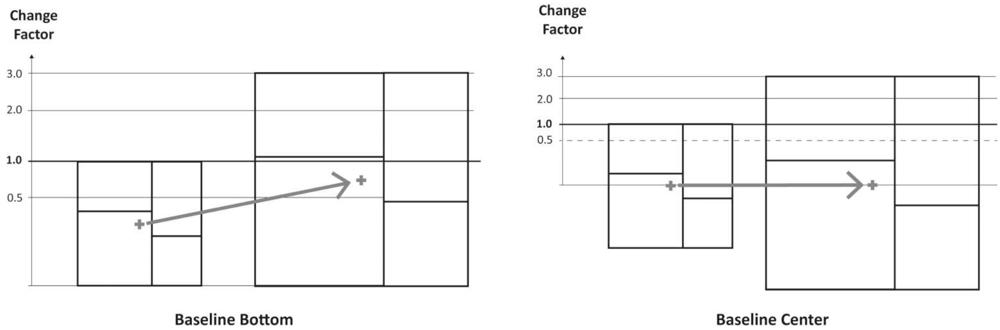

Figure 4. Diagram-like 'legend' for Total Change Maps – with different baselines.

small and standard-shaped representative samples are hard to transfer to the map image with irregular regions.

Hence, at least for the Total Change Maps we propose a diagram-like representation with a vertical axis to the left of the first map (in Ground Plan Alike representation and change factor 1) together with horizontal auxiliary lines, which enable an easier direct reading of change factors (Figure 4). This principle can also be easily applied with animations.

When fixing the maps at the bottom (Figure 4, left), there is the disadvantage that searching for one and the same area needs more bi-directional eye movements (indicated by the non-horizontal grey arrow). This can be critical, in particular, for putting map frames into an animation. When fixing the maps at their centres (Figure 4, right), eye movements are reduced at the cost of shrinking the resolution at the vertical axis by factor 2. Again, empirical studies are needed to figure out default solutions.

Implementing the principle of scaling spatial units into an animation, leads to the question of transitions or interpolation (morphing) between map frames (Fish et al., 2011) – a question that is beyond the scope of this paper and has to be postponed to later studies.

4. Exemplary application

4.1. Input data

This study uses a data set from the Robert Koch Institute (Berlin, Germany) – the description of daily Covid-19 incidences for the 16 federal states of Germany between September 11th, 2021 and April 17th, 2023. To reduce the data set, temporal aggregation was carried out by averaging daily to monthly values. For demonstration purposes a subset of months 4–8 was generated that describes five epochs, which are named epochs 1–5 in the following for simplification purposes (Table 1).

4.2. Data processing

As described in Section 3.2, the quotients Q_i are calculated for each state and month with respect to the corresponding first month. Applying different scaling functions (proportional with $c = 1$, exponential with $r = 1.5$ and range-graded) yield respective scalars Q_i' that are then multiplied with the original area size A_1 of each State, leading to the

Table 1. Used data set of monthly Covid-19 incidence values (source: https://www.rki.de/DE/Content/InfAZ/N/Neuartiges_Coronavirus/Daten/Inzidenz-Tabellen.html) – together with area sizes of states (in km^2, also area size of change maps at t = 1).

	Values v_i for months					
State	1	2	3	4	5	Area A_1
Baden-Württemberg	302	936	1519	1656	692	35751
Bayern	262	1085	1699	1938	822	70550
Berlin	343	1439	1044	939	461	892
Brandenburg	489	1125	1557	1285	514	29476
Bremen	403	1385	856	1362	901	404
Hamburg	325	1273	783	1009	805	755
Hessen	229	1104	1137	1314	859	21114
Mecklenburg-Vorp.	364	874	1522	2099	726	23173
Niedersachsen	177	752	1151	1670	1016	47616
Nordrhein-Westfalen	238	943	1234	1311	711	37082
Rheinland-Pfalz	206	714	1040	1512	782	19847
Saarland	268	946	1404	2099	972	2568
Sachsen	536	535	1231	1757	568	18413
Sachsen-Anhalt	490	641	1651	1748	680	20447
Schleswig-Holstein	233	843	853	1397	986	15761
Thüringen	634	427	1218	1971	614	16172
Total	**291**	**940**	**1314**	**1555**	**760**	**360021**

desired 'new areas' A_i. For this paper, scaling parameters c and r are results of iterative testing, with the general aim of demonstration purposes only.

For the case of range-graded scaling the determination of class breaks is required in a first step. Based on the value range of quotients Q_i (0.67–9.43) and the a-priori setting of four classes, class breaks are set at 1.0 (summarizing all decreases), 4.0 and 7.0 (producing a nearly equidistant grouping with 'round' values for increases). In a next step, each class has to be assigned with a common scaling factor Q_i'. A straightforward assignment uses the mean values between respective lower- and upper-class boundaries (i.e. the Q_i' values 0.83, 2.5, 5.5 and 8.21). Following the Sponge Map principle for emphasizing large changes (Schiewe, 2023a; Section 2), another map is also created with $Q_4' = 20.0$ (instead of 8.21) for the most upper class (and keeping the other Q_i' values constant).

For all scaling function cases and based on the respective Q_i' values, the adapted area values A_i can be computed. These build the input for the generation of the Value by Area Maps using the go-cart-tool (https://go-cart.io/), which is based on the Gastner algorithm (Gastner et al., 2018).

Considering the total sum of all 'new areas' A_i compared to the sum of all A_1 in epoch 1, the total quotient is calculated. This quotient is used to adjust the total size of the entire map size by applying the square root of the total factor for vertical and horizontal expansion, each – leading to the Total Change Maps. Applying the normalization as described in Section 3.3 (which is actually automatically done by the go-cart tool) leads to the Normalized Change Maps.

For the purpose of dual coding, a classification of original values takes place. This is guided by two demands (Section 3.4): insert at least one class break for large value changes (where Δ_{LARGE} is set to 1000) and avoid class changes for small value changes (Δ_{SMALL} is set to 100). Again, this parameter setting just serves for demonstration purposes and follows no statistical foundation yet. All value changes that are affected by these settings, are plotted as shown in Figure 5. Using a sweep line algorithm (with a predefined

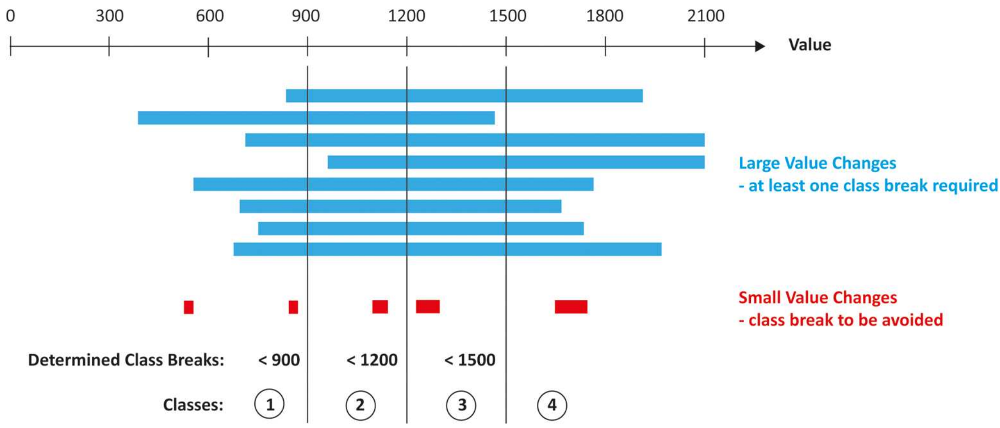

Figure 5. Data classification for original values.

number of four classes), one sweeps lines perpendicular to the number line ('Value'), looking for intersections with the blue boxes (representing large value changes) and no intersections with red boxes (small value changes). In this example, it is quite easy to find an optimal solution just by visual inspection where all conditions can be fulfilled.

4.3. Output maps

In the following the results after applying different scaling functions for Total and Normalized Change Maps are presented.

4.3.1. Proportional scaling

The TCM (Figure 6, top) makes the overall increase (until month 4) and decrease (from month 4 to 5) clearly visible. The single states behave in a similar manner; however, any deviations from the total behaviour change is hardly to identify. This is better visible in the NCM (Figure 6, bottom). For example, there are clear differences (marked with orange circles) for the states Bayern and Thüringen between epochs 1 and 2, or Niedersachsen between epochs 4 and 5.

Applying a scaling factor with $c \neq 1$ leads to a proportional increase or decrease of all spatial units and the total map size. As already obvious in Figure 1 (top right), this effect is visible when the corresponding display space is provided. Logically and due to numerical reasons, the NCM for $c \neq 1$ does not change compared to the case of $c = 1$.

4.3.2. Exponential scaling

Applying the exponential scaling, large changes are emphasized (marked with orange circles in Figure 7) that were not so clearly visible with the other options due to the small original areas. One also can make out disadvantages of this strong exaggeration as some states are heavily distorted (in particular, those that surround enlarged island states as mentioned above). With that, a fast and reliable search for single regions is not guaranteed in any case.

Figure 6. Proportional Scaling c = 1 – Total Change Map (top; total size proportional to total sum of values) and Normalized Change Map (bottom; total size constant) – orange circles point to conspicuous cases (compared to previous maps) as described in the text.

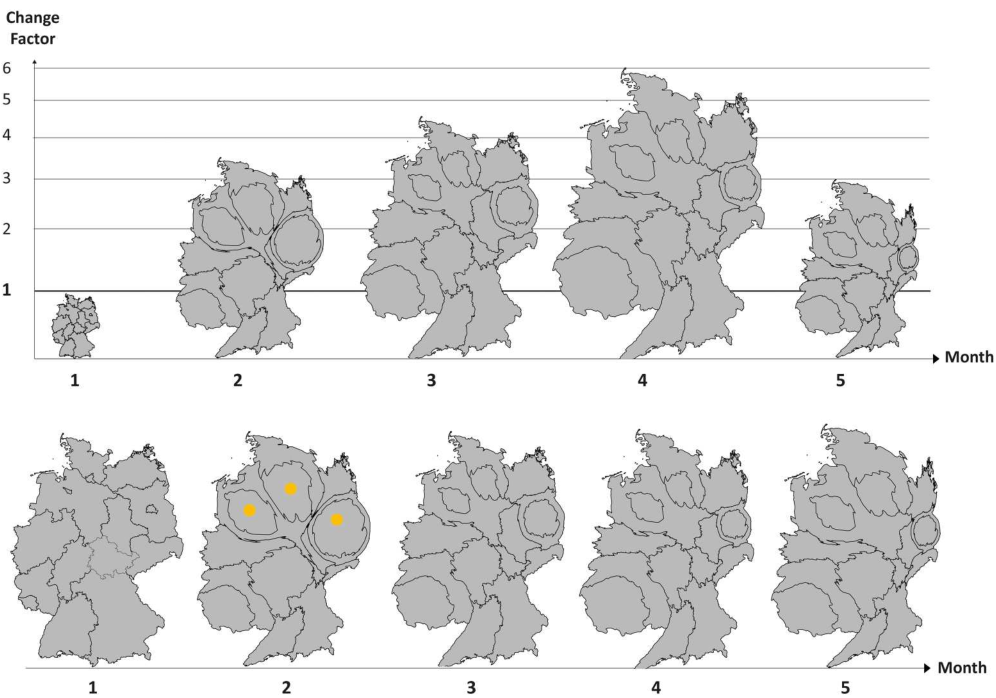

Figure 7. Exponential Scaling – Total Change Map (top) and Normalized Change Map (bottom) – orange circles point to conspicuous cases (compared to previous map) as described in the text.

4.3.3. Range graded scaling

The first version (Figure 8, top and middle), using Q_i' values 0.83, 2.5, 5.5 and 8.21 (i.e. without exaggeration; Section 4.2), shows only minor differences and accentuations compared to the proportional version with c = 1. However, applying the Sponge Map principle by increasing the Q_i' value for the upper class from 8.21 to 20, shows a very clear emphasis of large changes (marked with orange circles in Figure 8, bottom) – but again, at the cost of strongly distorting some regions.

4.3.4. Dual coding

Considering the above example with proportional scaling (c = 1), an additional colour lightness coding of the original values is created. Logically, in the TCM areas sizes and lightness behave in similar manner (e.g. an increase of area size normally goes along with a decrease of lightness, at least for large changes). The additional value of this dual coding lies in the ability to read off the

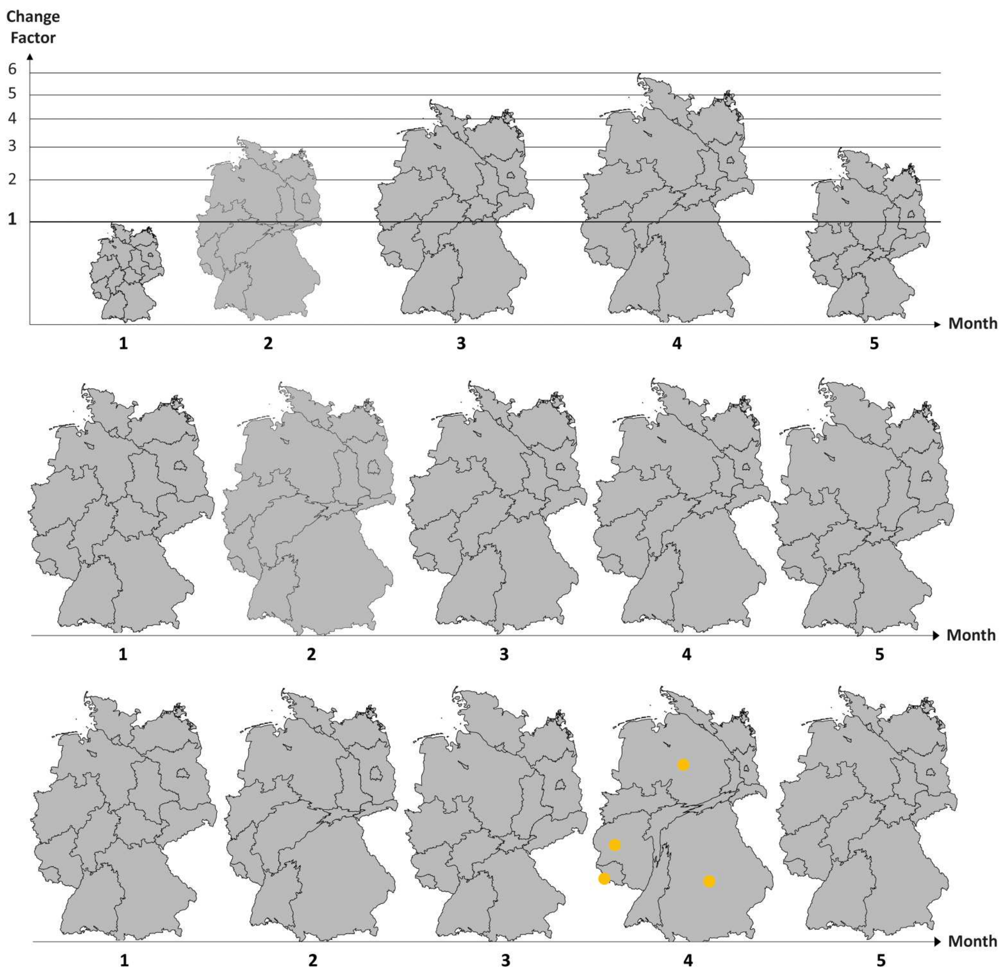

Figure 8. Range-graded scaling – Total Change Map (top) and Normalized Change Maps (middle) without emphasizing factor and NCM with emphasizing upper class (bottom) – orange circles point to conspicuous cases (compared to previous map) as described in the text.

Figure 9. Dual Coding (additionally coding absolute values by colour lightness) – Total (top) and Normalized Change Maps (bottom) – orange circles point to conspicuous cases (compared to previous map) as described in the text.

original values (better: their value interval) directly, which is nearly impossible for the area sizes alone. A further additional value of dual coding, however, can be seen with the exemplary marked states in the NCMs (Figure 9, bottom): they show the increase in relative share to the whole country (area size increases), but now also the decrease of original values (lightness decreases).

4.3.5. Center baseline

The examples so far followed the bottom baseline principle (Figure 4 left). Figure 10 (in comparison to Figure 9 top) demonstrates the difference to the centred baseline

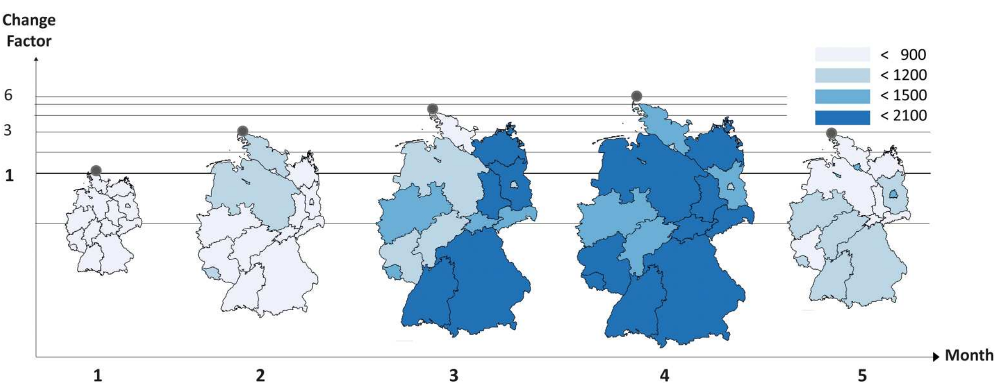

Figure 10. Centered baseline (around change factor 1) – Total Change Map (dual coding); additional reading off-points are integrated (see Section 6 for explanation).

(Figure 4 right). As explained before, the resolution of the vertical axis to the left is reduced by factor 2, which makes the reading of change factors much more difficult.

5. Preliminary study

An in-depth qualitative or even quantitative study about the intuitive understanding of this type of representation is beyond the scope of this paper. However, a very small preliminary qualitative study has been performed in order to get first impressions about the general feasibility as well as potential problems of the overall concept. According to Nielsen and Landauer (1993), five test persons are already sufficient to detect a relatively large number of basic problems. Of course, this preliminary study also served as preparation of a larger study that is currently under work.

Five persons (two with and three without background in Cartography) are interviewed with a simple questionnaire on paper, which was worked on independently and with free time management. Five output maps are shown and the participants should identify the direction of change and write down which information they can derive and which interesting or disturbing features they experienced. They got the information that the maps showed Covid numbers for German states over five months. Answers are given in free text format.

The following maps haven been presented to the participants (in this order):

- Map 1: Normalized Change Map: range-graded scaling (Figure 8, middle)
- Map 2: Total Change Map: range-graded scaling, (Figure 8, top – but without vertical axis, i.e. without information about change factors)
- Map 3: Total Change Map: exponential scaling, including vertical axis (Figure 7, top)
- Map 4: Normalized Change Map: exponential scaling (Figure 7, bottom)
- Map 5: Total change map: proportional scaling $c = 1$, dual coding (Figure 9, top)

Summarizing the participant's statements, the following conclusions can be drawn:

- Scaling functions. In principle, the intuitive association between the size of single regions or the total map and the underlying attribute values works (or at least in the course of the study). The strong distortions caused by the exponential scaling function lead to new interpretations, but especially for laypersons also to some confusion.
- Interpretation of NCM. The fact that only relative proportions are shown is usually recognized (or at least in the course of the study). After viewing the TCM in the meantime, the identical size of all NCM frames is not interpreted as identical total values (which is a correct conclusion).
- Interpretation of TCM. The fact that total values are displayed works. The addition of the vertical axis (with the labelling of the change factors) is found to be helpful. The multi-temporal interpretation of single units is seen as much more difficult.
- Dual coding. The common representation is seen as more attractive. Colour is obviously the dominant feature and important for recognizing larger spatial patterns (the latter in particular for experts).
- Graphical design. The design with regard to placing baseline and position of the reading points for single map frames is not yet clear enough. In particular, the read-off point for the total size is not intuitive enough.

6. Discussion

6.1. Scaling functions

The well-known use of size in graduated symbol maps as well as the statements in the preliminary study suggest that the concept of depicting change with spatial unit sizes is probably generally understood. Nevertheless, it is an unfamiliar representation that certainly requires a brief textual explanation. The stronger distortions (as with exponential scaling) lead to a conceptual dilemma: additional information can be derived (e.g. conspicuous changes for small regions); however, distortions are also perceived as disturbing when searching for specific states. This leads to the necessity to further develop the already mentioned idea of Sponge Maps, i.e. to create a case-specific compromise between emphasising certain changes and preserving legibility. In this context, it should also be emphasised that there is of course not the one and only one correct scaling function for all scenarios.

6.2. Normalized change map

In the preliminary study, the interpretation of the NCMs has intuitively and correctly focused on the relative relationships between the units. At the same time, however, it should be clarified with explanatory text that total numbers cannot be derived.

6.3. Total change maps

The preliminary study suggests that in TCMs the correct association of the total size with the total attribute values seems to take place. The evaluation of individual regions is logically more difficult due to the changes in overall size. If this aspect is also required in the application, a stronger distortion through the scaling function can provide a remedy. For TCMs in particular, further map design elements need to be tested for a better understanding (see below).

6.4. Dual coding

Surprisingly, the increased complexity due to dual coding has not been critically noted by the participants of the preliminary study; instead, the increased attractiveness has been emphasised. However, it seems that the additional information content (i.e. coding of the original values) has not been recognized (at least not explicitly).

6.5. Map design

The introduction of the vertical axis for TCMs is probably very helpful. Obviously, however, there is still room for improvement or at least investigation: firstly, the centring of the baseline (and the subsequent bi-directional expansion) can make it clear that the size changes relate to the areas (and not to height only). Secondly, the read-off position (at least for the bottom baseline variant) is unclear – additional coding (via data points at the northern tip of the country's outline, Figure 10, or even a corresponding line diagram) could be helpful here.

7. Summary and conclusions

Subject of this paper was the introduction of an alternative concept of using spatial unit scaling for displaying quantitative and area-based change information. This idea is based on the concept of Value by Area Maps, which has so far only been used for mono-temporal maps. The new concept includes the use of different scaling functions (proportional, exponential, range-graded) that are able to highlight different change information. Furthermore, the distinction is made between Total Change Maps (i.e. the total map size is changed according to the total value change) and Normalised Change Maps (i.e. the total map size is kept constant over all epochs). Finally, the integration of original value data is possible by dual coding (including an a priori data classification that preserves changes).

A small, preliminary qualitative study leads to the hope of a general intuitive understanding of the concept of linking value changes with spatial unit size changes. But it also revealed further necessities, including the integration of brief textual explanations, the consideration of other graphical variants (concerning baseline, highlighting read-off positions, etc.). All this has to be flanked with in-depth empirical studies, which, among others, try to answer the following research questions:

- Beyond the understanding as such, does the coding of value changes by changing spatial unit sizes also lead to a more effective and efficient perception than coding by symbol sizes or lightness?
- How can the problem of distortions be countered? A critical problem with Value-by-Area Maps is the tracing of individual spatial units (e.g. countries) over time, which is complicated by the inherent size distortion. One approach to reduce this effect could be to use different colours for each unit, which then remain the same over time.
- How are users actually work on Sponge Maps? In order to understand user behaviour while working on multi-temporal Sponge Maps, eye tracking analysis with very high spatial resolution could be of great help.
- What is the minimum of textual explanations for expert and layperson users for different types of maps (TCM, NCM, Dual Coding)? In a first attempt, these explanations should be placed in a prominent position (e.g. as a sub-title) – e.g. for TCMs: 'Size of federal states changes according to change in Covid values from month to month'.
- Is it possible to define a clear association between scaling function and application of the Sponge Maps principle to deliver a good compromise between highlighting important changes and avoiding disturbing distortions (e.g. based on statistical properties of the data set or the specific change task)?
- Is dual coding increasing effectiveness and efficiency of information extraction regarding change and original values?
- In the case of Total Change Maps, are there limits regarding maximum ratios between total maps sizes (depending on available display space and cartographic minimum dimensions)?
- How should the parameters be controlled when creating the Sponge Maps? It has to evaluated to what extent the end user is responsible for parameter settings (based on specific tasks), or whether some parameters can be derived from statistical properties of a given data set (e.g. maximum change rate in values together with minimum

and maximum available display size for TCM might lead to default setting of scaling function).

In the overall context of improving the usability of multi-temporal maps, the contribution of this work can be summarized as follows:

- The introduction of the concept is meant to initiate discussion and research about alternative coding of change information in order to react to the increasing amount of multi-temporal geodata and the demand for more usable cartographic display.
- The presented concept makes it possible to convey different types of change information (e.g. change quotients of single or total areal units or values as such) – either in an isolated, or in a combined manner.
- It is of special interest to use different scaling functions (or parameter settings for them) in order to find a compromise between emphasizing certain changes and preserving legibility.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

Data used in the experiments were presented in Section 4.1.

Notes on contributor

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