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ROZPRAWA DOKTORSKA

METODYKA ZWIĘKSZANIA POTENCJAŁU INFORMACYJNEGO ORAZ PÓŁAUTOMATYCZNEGO OPRACOWYWANIA TYFLOMAP

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METODYKA ZWIĘKSZANIA POTENCJAŁU INFORMACYJNEGO ORAZ PÓŁAUTOMATYCZNEGO OPRACOWYWANIA TYFLOMAP

Osoby niewidome i słabowidzące (ONS) czytają mapy dotykiem i/lub w ograniczonym stopniu uszkodzonym wzrokiem, które mają znacznie niższą rozdzielczość niż wzrok nieuszkodzony. Dlatego też opracowywane dla nich mapy (tyflomapy) mają mocno uogólnioną treść – pojedynczy arkusz mapy przekazuje niewielką ilość informacji. Opracowywanie takich map jest skomplikowane i czasochłonne, zaś koszty produkcji bardzo wysokie. Ponadto, istniejące dotychczas rozwiązania automatycznego generowania tyflomap nie uwzględniały właściwej generalizacji danych przestrzennych, przez co wynikowe mapy były nieczytelne. Brakowało także rozwiązań do automatycznego generowania tyflomap tematycznych. Wynika to między innymi z ograniczeń wykorzystywanych dotychczas metod produkcji, ale także braku jednoznacznych wytycznych dotyczących sposobu opracowywania tyflomap.

Przeprowadzone prace wstępne umożliwiły mi zidentyfikowanie problemów badawczych związanych z opracowywaniem tyflomap, które rozwiązałem w ramach cyklu składającego się z pięciu powiązanych tematycznie artykułów naukowych. W swojej rozprawie zaproponowałem metodykę obejmującą dwa podstawowe zagadnienia: zapewnienie wyższego potencjału informacyjnego tyflomap oraz zdefiniowanie jednoznacznych zasad opracowywania tyflomap tematycznych wraz z automatyzacją części etapów tego procesu.

Wysoki potencjał informacyjny map uzyskałem bazując na zasadach semiotyki i modyfikując sposób projektowania znaków tyflokartograficznych, poprzez wykorzystanie pełnego zakresu zmiennych haptycznych i graficznych, w tym różnicowania wysokości znaków. Udowodniłem, że dzięki dowolności w projektowaniu i druku znaków tyflokartograficznych, którą zapewnia technika druku 3D, możliwe jest zwiększenie ilości informacji przekazywanych za pomocą pojedynczych znaków (aspekt semantyczny), a w konsekwencji także całej tyflomapy, oraz uzyskanie lepszej czytelności jej rysunku. Wykonałem eksperyment, dzięki któremu wykazałem, że możliwe jest zmniejszenie odstępów pomiędzy elementami treści mapy do poziomu 1 mm z dotychczas rekomendowanych 3-5 mm (aspekt syntaktyczny), co umożliwiło umieszczenie więcej treści na mapie, a w konsekwencji, zwiększyło ilość informacji przekazywanych za pomocą tyflomapy. Do oceny ilości tej informacji wykorzystałem wartość informacyjną. Wartość tę wyznaczyłem za pomocą dwóch miar wykorzystywanych w klasycznej kartografii – strukturalnej miary informacji oraz współczynnika wydajności informacyjnej, które zaadaptowałem na potrzeby oceny tyflomap. Wykazałem, że zaproponowane przeze mnie rozwiązania zwiększają wartość obu tych miar, natomiast czytelność i użyteczność wynikowych tyflomap potwierdziłem w trakcie testów z udziałem ONS, wykorzystując metody sondażu diagnostycznego.

W celu zdefiniowania jednoznacznych zasad opracowywania tyflomap tematycznych wykorzystałem metody krytycznej oraz systematycznej analizy literatury, jak również analizy i syntezy, żeby zaproponować sposób postępowania przy opracowywaniu tyflomap. Zdefiniowałem optymalne kryteria redakcji kartograficznej (uwzględniające generalizację), jak również parametry mające wpływ na czytelność map. Rozwiązania te bazują na zagadnieniu warstw kotwiczących (anchor layers), które wykorzystałem do przygotowania treści podkładowej, do której następnie dopasowywane są treści tematyczne. Precyzyjnie zdefiniowałem mierzalne parametry dotyczące zarówno cech geometrycznych znaków tyflokartograficznych, jak i redakcji treści mapy, które mają wpływ na czytelność i powinny być dobierane pod kątem konkretnej techniki druku (w tym przypadku druku 3D). W procedurze opracowywania tyflomapy zaimplementowałem moje rozwiązania zwiększające wartość informacyjną oraz zaproponowałem algorytmy umożliwiające pełną automatyzację najtrudniejszych etapów związanych z generalizacją danych przestrzennych, w tym selekcję, wygładzanie, wyrównywanie i przesuwanie elementów treści tyflomap.

Weryfikację metodyki przeprowadziłem opracowując prototyp hybrydowej tyflomapy, składający się z przezroczystej warstwy dotykowej dla osób niewidomych i wysoce kontrastowej warstwy graficznej dla osób słabowidzących. Prototyp zweryfikowałem podczas sesji badawczych z udziałem ONS, które potwierdziły jego czytelność i użyteczność. Uzyskane wyniki potwierdziły, że wykorzystanie dodatkowych zmiennych haptycznych zwiększa wartość informacyjną tyflomap, zaś parametryzacja procesu opracowywania mapy umożliwia automatyzację jego najtrudniejszych etapów, zapewniając powtarzalność generowanych tyflomap.

Zaproponowana przeze mnie metodyka znacznie redukuje subiektywność opracowywania tyflomap tematycznych oraz obniża koszty ich produkcji i czas opracowywania. Ponadto, może być w łatwy sposób modyfikowana i parametryzowana na potrzeby innych opracowań kartograficznych, dzięki czemu generowanie tyflomap w przyszłości będzie łatwiejsze, szybsze i tańsze niż dotychczas, co przełoży się na ich większą dostępność dla ONS.

METHODOLOGY FOR INCREASING THE INFORMATION VALUE POTENTIAL AND SEMI-AUTOMATIC TACTILE MAPS DEVELOPMENT

People with visual impairments (PVI) read maps using their sense of touch or, to a limited extent, damaged sight, that are characterised by a much lower resolution than that of a person without visual impairments. Therefore, the maps developed for PVI (called tactile maps), have highly simplified content – a single map sheet conveys a small amount of information. The development process of such maps is complicated, expensive and time-consuming. Moreover, the existing solutions for the automatic generation of tactile maps do not consider the proper generalisation of spatial data and thus, the resulting maps are illegible by PVI. There was also a lack of solutions for the automatic generation of thematic tactile maps. This is due, inter alia, to the limitations of the hitherto used production methods but also due to the lack of unequivocal guidelines on how to develop tactile maps.

The preliminary research that I carried out allowed me to identify research problems related to the development of tactile maps that I solved in a cycle of five thematically related research papers. In my dissertation, I proposed a methodology covering the two main issues: ensuring a higher information potential of tactile maps and defining unambiguous rules for the development of thematic tactile maps along with the automation of the selected stages of this process.

I obtained the high informational potential of maps basing on the principles of semiotics and by modifying the way of designing signs on tactile maps as well as using the full range of haptic and graphic variables, including the height differentiation of signs. I have proved that thanks to the freedom in designing and printing of signs on tactile maps, which is provided by the 3D printing technique, it is possible to increase the amount of information transmitted by single signs (semantic aspect) and, consequently, the whole tactile map, as well as to obtain its better legibility. I carried out the experiment that helped me prove that it is possible to reduce the spacing between map content elements to 1 mm from the 3-5 mm recommended so far (syntactic aspect), which allowed to place more content on the map sheet and, consequently, increased the amount of information provided by the tactile map. I used the concept of information value to estimate the amount of this information. I calculated this value by applying two measures used in classic cartography – the structural measure of information and the information efficiency coefficient, which I adapted for the purpose of tactile maps assessment. I have shown that

the solutions I propose increase the value of both of these measures, while the legibility and utility of the resulting tactile maps were confirmed during study sessions with the participation of PVI, using the diagnostic survey method.

In order to define unequivocal rules for the development of thematic tactile maps, I applied the methods of critical and systematic literature review, as well as analysis and synthesis, to propose the procedure for their development along with the optimal criteria for cartographic editing (taking into account generalisation), as well as parameters impacting the map's legibility. These solutions are based on the concept of anchor layers that I used to prepare the background content, to which the thematic content is then adjusted. I precisely defined the measurable parameters concerning both: the geometrical properties of the signs on tactile maps and the cartographic editing of the map content, which affect the legibility and should be adjusted to the selected printing technique (in this case 3D printing). In the tactile map development procedure, I implemented my solutions for increasing the information value and proposed the algorithms enabling full automation of the most difficult stages related to the generalisation of spatial data, including selection, smoothing, aligning and displacement of tactile map content.

I verified the methodology by developing a prototype of a hybrid case study tactile map, consisting of a transparent tactile overlay for the blind and a highly contrasting graphic underlay for the visually impaired. The prototype was verified during study sessions with PVI, confirming its legibility and utility. The obtained results confirmed that the use of additional haptic variables increases the information value of tactile maps, whereas parametrization of the map development process enables the automation of its most difficult stages, ensuring the repeatability of the generated maps.

The methodology I proposed significantly reduces the subjectivity of the development of thematic tactile maps and lowers the costs and time related with their production. In addition, it can be easily modified and parameterized for the needs of other cartographic elaborations, thanks to which the generation of tactile maps in the future will be easier, faster and cheaper than before, which will result in their greater availability for PVI.

SPIS TREŚCI

WYKAZ UŻYTYCH SKRÓTÓW

- **FDM** – *ang. Fused Deposition Modelling*, technologia druku 3D polegająca na wytapianiu plastycznego materiału na stole drukarki warstwa po warstwie
- **GUGiK** – Główny Urząd Geodezji i Kartografii
- **ICA** – *ang. International Cartographic Association*, Międzynarodowa Asocjacja Kartograficzna
- **ONS** – osoby niewidome i słabowidzące
- **SLA** – *ang. stereolitography*, technologia druku 3D polegająca na utwardzaniu kolejnych warstw termoutwardzalnych ciekłej żywicy za pomocą promieniowania ultrafioletowego
- **WHO** – *ang. World Health Organization*, Światowa Organizacja Zdrowia

1. WPROWADZENIE

Według Bieleckiej i Maja (2009), ponad dekadę temu 80% danych wykorzystywanych w administracji publicznej w Polsce posiadało odniesienie przestrzenne. Można założyć, że obecnie ten odsetek jest jeszcze wyższy. Najlepszym zaś sposobem na prezentację danych przestrzennych są mapy. Współcześnie wykorzystuje się głównie mapy cyfrowe, które często można generować w sposób automatyczny oraz szybko edytować i aktualizować. Niestety, mapy cyfrowe nie są przystosowane do czytania przez osoby niewidome i słabowidzące (ONS). Dla tej grupy odbiorców projektuje się specjalny rodzaj map, które czytane są z wykorzystaniem zmysłu dotyku i/lub, w ograniczonym stopniu, wzroku. Są to tyflomapy, zaś osoby zajmujące się opracowywaniem tyflomap określa się mianem tyflokartografów.

Tyflomapy muszą zostać przygotowane w taki sposób, aby mogły być przeczytane przez ONS. Żeby osoba niewidoma mogła wyczuć elementy mapy palcami, ich treść musi być wypukła – dotykowa. Z kolei dla osób słabowidzących opracowuje się specjalne, silnie uogólnione mapy z intensywną kolorystyką. Jeszcze do niedawna badania z zakresu tyflokartografii były rzadko podejmowane. Wśród badaczy panowało przekonanie, że grono odbiorców jest niewielkie, a same badania są bardzo skomplikowane. Jednak od ponad dekady sytuacja się zmienia, głównie ze względu na większą świadomość społeczną w zakresie potrzeb osób z niepełnosprawnościami oraz rosnącą popularność szeroko rozumianej dostępności i rozwiązań zgodnych z zasadami projektowania uniwersalnego.

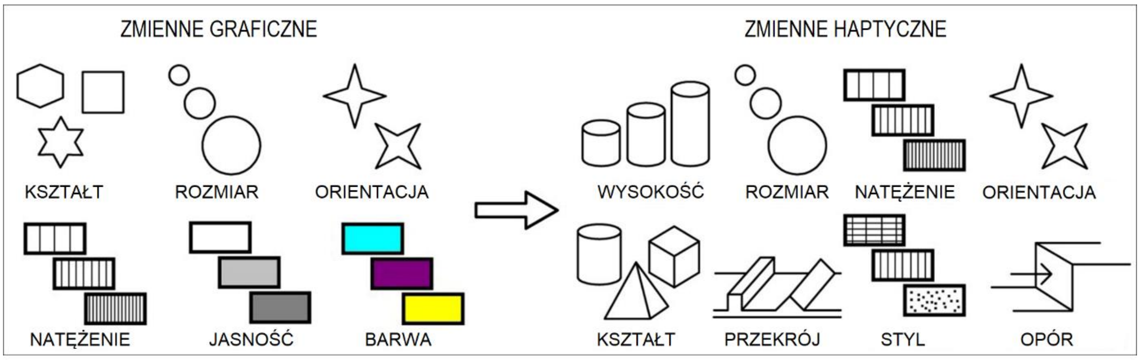
Szacuje się, że na świecie są 253 miliony osób z poważną dysfunkcją wzroku, z czego 36 milionów to osoby niewidome. Z kolei zjawisko starczowzroczności, czyli utraty ostrości widzenia wraz z wiekiem, dotyczy 1,1 miliarda ludzi (Ackland, Resnikoff, & Bourne, 2017). Główny Urząd Statystyczny podaje, że w Polsce liczba osób z dysfunkcjami wzroku wynosi łącznie 1,8 miliona, z czego 100 tysięcy to osoby niewidome[1] (Główny Urząd Statystyczny, 2011). Mimo zwiększania świadomości społeczeństw na temat wyzwań, jakie stoją przed osobami o szczególnych potrzebach,

[1] Z punktu widzenia polskiego prawa, osobą niewidomą jest osoba, u której ostrość wzroku wynosi mniej niż 10% pełnej ostrości wzroku, lub osoba, której pole widzenia wynosi nie więcej niż 30 stopni (pełne pole widzenia wynosi około 180 stopni) (BON Uniwersytetu Warszawskiego, 2017).

problemy ONS są marginalizowane, natomiast **liczba osób z dysfunkcją wzroku jest stosunkowo duża i będzie rosła, wraz ze starzeniem się społeczeństw**.

Jak wykazały badania, zdolność palca do rozróżniania pojedynczych obiektów jest około 10 razy gorsza niż oka (Klatzky & Lederman, 2003; Yanoff & Duker, 2009). Przeciętna osoba bez zaburzeń wzroku, jest w stanie odróżnić w normalnych warunkach dwa punkty lub linie, jeśli znajdują się one w odległości co najmniej 0,15 mm od siebie (Yanoff & Duker, 2009). Aby rozróżnić dwa punkty jako oddzielne z wykorzystaniem dotyku, muszą się one znajdować w odległości przynajmniej 2,4 mm (Klatzky & Lederman, 2003). Zatem, aby przekazać tę samą ilość informacji, jaka znajduje się na klasycznej mapie, jej dotykowy odpowiednik (tyflomapa) powinien być w przybliżeniu 10 razy większy. Taka mapa byłaby jednak niewygodna do czytania dotykiem - przyjmuje się, że prawidłowo zaprojektowana tyflomapa powinna być możliwa do objęcia ramionami przez siedzącego czytelnika, czyli w praktyce, mieć wymiary nieprzekraczające 50 na 50 centymetrów. Na mapie o takich rozmiarach **zmieści się niewiele elementów,** co wynika z faktu, że **aby treść takiej mapy mogła być przeczytana dotykiem, musi być znacznie uogólniona**, czyli silnie zgeneralizowana. Generalizacja zaś jest jednym z najbardziej skomplikowanych zadań w kartografii, między innymi z uwagi na trudność w wyselekcjonowaniu obiektów, które powinny zostać uproszczone lub wręcz usunięte na uogólnionej mapie (Chrobak, 2003), nie powodując przy tym znaczącej utraty dokładności (Bakuła et al., 2013).

Stosując duże uogólnienie treści mapy, które wynika bezpośrednio z ograniczeń percepcyjnych zmysłu dotyku, niezwykle istotna jest optymalizacja treści tyflomap, czyli taki dobór jej elementów, by odbiorca z dysfunkcją wzroku mógł je swobodnie przeczytać. Jednocześnie, należy przekazać odbiorcy jak najwięcej informacji przestrzennej, z wykorzystaniem ograniczonej liczby silnie uproszczonych znaków zbudowanych ze zmiennych graficznych i haptycznych – związanych ze zmysłem dotyku (Rys. 1.).



Rys. 1. Zmienne graficzne oraz haptyczne

Pojęcie zmiennych graficznych zostało wprowadzone przez Bertina już przeszło pół wieku temu (Bertin, 1967). W przeszłości wielu badaczy analizowało potencjał zmiennych graficznych w kontekście projektowania znaków kartograficznych (Carpendale, 2003; Garlandini & Fabrikant, 2009; Maceachren, 2004), jednak pojęcie zmiennych haptycznych jest badane od stosunkowo niedawna (Griffin, 2001) i nadal trwają prace nad optymalizacją ich wykorzystania (McCallum, Ahmed, Jehoel, Dinar, & Sheldon, 2005; Wabiński, Śmiechowska-Petrovskij, & Mościcka, 2022). Zadanie to jest o tyle skomplikowane, że w przypadku percepcji dotykowej nie można korzystać z najbardziej sugestywnej zmiennej graficznej - barwy.

Czytelność tyflomap jest ich najważniejszą cechą. Projektując tyflomapy niejednokrotnie odchodzi się od matematycznych podstaw kartografii, aby zagwarantować jak najłatwiejszy odbiór treści, np. stosuje się nieokrągłe mianowniki skali mapy. Głównym czynnikiem obniżającym ich czytelność jest zbyt duża złożoność materiałów tyflograficznych. W przypadku tyflomap, częstym błędem jest adaptacja map klasycznych bez odpowiednio przeprowadzonej generalizacji (Zebehazy & Wilton, 2014). W rezultacie, blisko 47% uczniów niewidomych nie jest w stanie nadążyć za rówieśnikami widzącymi podczas rozwiązywania zadań w klasie (Śmiechowska-Petrovskij, 2015). Tyflokartografowie stoją więc przed wyzwaniem, **w jaki sposób zapewnić jak najwyższą czytelność map, ale jednocześnie przekazać za ich pomocą jak najwięcej informacji**. Jest to zadanie trudne, a co za tym idzie czasochłonne, zaś **uzyskiwane wyniki są w dużej mierze subiektywne**, zależne od umiejętności i doświadczenia tyflokartografa.

Chociaż zapewnienie wysokiej czytelności tyflomap jest najważniejsze, to nie można całkowicie odchodzić od standardów kartograficznych. Aby opracować kartometryczną i funkcjonalną mapę, należy wykorzystać wiarygodne dane przestrzenne oraz zweryfikowane algorytmy generalizacji kartograficznej. Te algorytmy odpowiadają za poprawne uproszczenie elementów treści mapy i właściwy sposób ich prezentacji. Opracowanie takich algorytmów stanowi wyzwanie w przypadku map klasycznych, które komplikuje się jeszcze bardziej, jeśli mają one być zaimplementowane do generowania tyflomap, co jest związane bezpośrednio z opisanymi wcześniej ograniczeniami zmysłu dotyku i uszkodzonego wzroku.

Kolejnym problemem związanym z opracowywaniem tyflomap jest **bardzo duże zróżnicowanie zdolności percepcyjnych osób z dysfunkcjami wzroku oraz mnogość metod reprodukcji tyflomap o zróżnicowanej charakterystyce** (Brittell, Lobben, & Lawrence, 2018). Zdolności percepcyjne są zależne między innymi od momentu utracenia widzenia, jak i poziomu doświadczenia w pracy z materiałami tyflograficznymi. Natomiast czynniki takie jak cukrzyca, czy nadmierne stosowanie środków do dezynfekcji dłoni, mogą wpływać na obniżoną czułość opuszków palców (Edman, 1992).

Ponadto, na sposób opracowania tyflomapy ma wpływ jej przeznaczenie: mapa do orientacji i nawigacji czy mapa tematyczna, mapa na stałe zamontowana na pulpicie czy podręczna, przeznaczona dla dzieci czy osób dorosłych? Powyższe czynniki są główną przeszkodą na drodze do sprawnego redagowania i reprodukcji tyflomap. Wynika to także z **braku szczegółowych zasad opracowywania tyflomap** (Cole, 2021; Fleming, 1990). Istniejące w różnych krajach wytyczne i standardy nie uwzględniają wszystkich aspektów redakcji tyflomap, w tym ich generalizacji. Najczęściej stanowią zbiór zaleceń, a produkt finalny jest luźną interpretacją wytycznych przez osobę opracowującą tyflomapę. Nawet jeśli w wytycznych podawane są konkretne parametry, to zazwyczaj brakuje informacji, dla jakich technik reprodukcji mają one zastosowanie. W efekcie, różni redaktorzy tyflomap, korzystający z tych samych wytycznych, mogą opracować dwie różne tyflomapy, **nie zapewniając powtarzalności i równoważnej jakości.**

Niestety, mimo ostatnich postępów w rozwoju tyflokartografii, **opracowywanie tyflomap jest w dalszym ciągu kosztowne i czasochłonne** (Ducasse, Macé, & Jouffrais, 2015), a nakłady atlasów tematycznych publikowanych w Polsce przez Główny Urząd Geodezji i Kartografii (GUGiK) są niewielkie, mimo wysokiego zapotrzebowania na takie materiały w ośrodkach, gdzie kształci się ONS. W dużej mierze wynika to z faktu, że **tradycyjne metody produkcji tyflomap** (wykorzystywane między innymi przez GUGiK) **są opłacalne tylko w przypadku produkcji na dużą skalę.** Techniki termoformowania czy sitodruku wypukłego wymagają przygotowania drogich matryc. Alternatywnym rozwiązaniem są chociażby mapy drukowane na papierze puchnącym, jednak możliwości projektowania znaków na tego typu mapach, jak również ich trwałość, są mocno ograniczone (Brittell et al., 2018; Voženílek et al., 2009).

Niska dostępność tyflomap jest tym większym problemem, że w Polsce podstawa programowa z zakresu geografii jest taka sama dla dzieci widzących, jak i niewidomych. Jednak dostęp do wysokiej jakości tyflomap jest nieporównywalnie trudniejszy, niż do ich klasycznych odpowiedników. Poza tym, czasami wymagane są pojedyncze arkusze tyflomap, przedstawiające konkretne zagadnienia, jak chociażby mapy prezentujące „małą ojczyznę", która jest jednym z elementów programu nauczania geografii, a atlasy przygotowywane przez organy państwowe to publikacje ujednolicone na poziomie całego kraju. Mimo długiej tradycji opracowywania tyflomap przez GUGiK, nadal **występuje niedobór materiałów edukacyjnych dla ONS.** W krajach słabiej rozwiniętych niż Polska (ale także w wielu państwach rozwiniętych), te braki są często jeszcze bardziej widoczne.

2. TYTUŁ ROZPRAWY, CEL, TEZA, CYKL PUBLIKACYJNY

Rozprawę doktorską pt. „Metodyka zwiększania potencjału informacyjnego oraz półautomatycznego opracowywania tyflomap" stanowi cykl pięciu powiązanych tematycznie artykułów naukowych. Cykl publikacji zawiera autorskie propozycje rozwiązań w obszarze usprawniania procesu opracowywania i druku tyflomap, zwiększania wartości informacyjnej takich map oraz automatyzacji ich generowania. Proponowane rozwiązania metodyczne zweryfikowałem na przykładzie tyflomap tematycznych, wykorzystując technikę druku 3D. Niniejsza rozprawa wpisuje się w światowe trendy poszukiwania nowych zastosowań informacji przestrzennej i zwiększania inkluzywności opracowań kartograficznych, poszerzając grono jej użytkowników o osoby z niepełnosprawnościami.

W swojej pracy zająłem się rozwiązaniem dwóch głównych problemów badawczych, związanych z opracowywaniem tyflomap. **Pierwszy z nich dotyczy niewielkiej ilości informacji przekazywanej za pomocą tyflomap**. Na ilość tej informacji mają wpływ dwie podstawowe składowe: liczba elementów rysunku kartograficznego oraz ilość informacji przekazywanych za pomocą znaków kartograficznych (Potelarska-Walczyńska, 1979). Wynikają one ze stopnia generalizacji rysunku treści mapy oraz sposobu wykorzystania zmiennych graficznych i haptycznych w konstrukcji systemu znaków tyflokartograficznych, zarówno w kontekście kodowania informacji przekazywanej przez znaki, jak i relacji między znakami. Dotychczasowe metody druku tyflomap nie umożliwiały jednak pełnego wykorzystania zmiennych haptycznych. Przyjąłem, że druk 3D może wyeliminować ten problem, gdyż umożliwia wydrukowanie dokładnie takiego modelu mapy, jaki został zaprojektowany (Wabiński & Mościcka, 2017).

Drugi problem badawczy dotyczy braku powtarzalności opracowywanych tyflomap. Przyjąłem, że powtarzalność tę można uzyskać dzięki ujednoliceniu zasad opracowywania tyflomap w taki sposób, żeby każdy opracowywał je według tych samych, jednoznacznych wytycznych. Wymaga to dokładnego sprecyzowania przede wszystkim parametrów związanych z projektowaniem znaków i redakcją mapy, które mają wpływ na jej czytelność i wynikają z przyjętej techniki druku. Ujednolicenie zasad przygotowywania tyflomap daje w konsekwencji możliwość automatyzacji wybranych etapów ich opracowywania.

W związku z powyższym podczas prac przyjąłem następujące założenia, z których wszystkie przekładają się także na redukcję czasu opracowywania tyflomap i kosztów z tym procesem związanych:

- technika druku 3D została zaprojektowana z myślą o szybkim prototypowaniu. Nowe rozwiązania w zakresie projektowania tyflomap można weryfikować szybciej i taniej, niż z wykorzystaniem klasycznych technik reprodukcji;
- dzięki wykorzystaniu nowoczesnej metody reprodukcji tyflomap (druku 3D) można wyeliminować ograniczenia w różnicowaniu znaków tyflokartograficznych. Możliwe jest lepsze wykorzystanie potencjału zmiennych haptycznych, w tym różnicowania wysokości znaków dotykowych;
- zoptymalizowany pod kątem wartości informacyjnej projekt tyflomapy umożliwia umieszczenie więcej treści na mapie, przy jednoczesnym zachowaniu jej czytelności;
- aby zapewnić powtarzalność i zagwarantować wysoką jakość wszystkich opracowań tyflokartograficznych, niezbędna jest parametryzacja procesu opracowania mapy.

Założenia te umożliwiły mi postawienie następującej tezy badawczej: **wykorzystanie pełnego potencjału zmiennych haptycznych oraz parametryzacja procesu opracowywania tyflomap zapewnia powtarzalne generowanie tyflomap o wyższej wartości informacyjnej**. Aby ją udowodnić, postawiłem sobie następujące główne cele badawcze:

1) **zaproponowanie sposobu zwiększania wartości informacyjnej tyflomap**, aby możliwe było przekazywanie za ich pomocą większej ilości informacji, bez negatywnego wpływu na czytelność;
2) **zdefiniowanie zasad półautomatycznego opracowywania tyflomap tematycznych**, w celu zapewnienia ich powtarzalności i równoważnej jakości.

W ramach powyższych celów głównych sformułowałem następujące cele szczegółowe:

a) zaproponowanie metody oceny wartości informacyjnej tyflomap;
b) opracowanie zasad wysokościowego różnicowania znaków na tyflomapach;
c) zdefiniowanie wytycznych i parametrów umożliwiających standaryzację procesu redakcji i reprodukcji tyflomap;
d) zaproponowanie metodyki opracowywania tyflomap z wykorzystaniem druku 3D.

Badania stanowiące podstawę niniejszej rozprawy doktorskiej zostały przedstawione w powiązanych tematycznie artykułach naukowych, opublikowanych w czasopismach wyróżnionych w *Journal Citation Reports*. **Suma punktów MEiN za publikacje uwzględnione w cyklu wynosi 470, a sumaryczny Impact Factor czasopism to 11,884 (z uwzględnieniem % udziału: punkty – 326, IF – 8,253).**

Lp.	ARTYKUŁ Z CYKLU	Punkty wg. MEiN, IF
1	**Wabiński, J.** (80%), Mościcka A. (20%) (2019) Automatic (tactile) map generation—a systematic literature review. *ISPRS International Journal of Geo-Information*, *8*(7). DOI: 10.3390/ijgi8070293	70 pkt., IF = 3,099
2	**Wabiński, J.** (70%), Mościcka, A. (20%), & Kuźma, M. (10%) (2020). The Information Value of Tactile Maps: A Comparison of Maps Printed with the Use of Different Techniques. *The Cartographic Journal*, *58*(2), 123–134. DOI: 10.1080/00087041.2020.1721765	100 pkt., IF = 1,311
3	**Wabiński, J.** (60%), Śmiechowska-Petrovskij, E. (30%), & Mościcka, A. (10%) (2022). Applying height differentiation of tactile signs to reduce the minimum horizontal distances between them on tactile maps. *PLOS ONE*, *17*(2). DOI: 10.1371/journal.pone.0264564	100 pkt., IF = 3,754
4	**Wabiński, J.** (70%), Mościcka, A. (20%), & Touya, G. (10%) (2022). Tactile maps design guidelines standardization: literature and best practices review. *The Cartographic Journal*. DOI: 10.1080/00087041.2022.2097760	100 pkt., IF = 1,366
5	**Wabiński, J.** (70%), Touya, G. (20%), & Mościcka, A. (10%) (2022). Semi-automatic development of thematic tactile maps. *Cartography and Geographic Information Science*. DOI: 10.1080/15230406.2022.2105747	100 pkt., IF = 2,354

Ze względu na rozpatrywane w cyklu problemy i cele badawcze, powyższe publikacje podzieliłem na dwie grupy:

1. problem badawczy 1: niewielka ilość informacji przekazywana za pomocą tyflomap [publikacje 1 i 2];
2. problem badawczy 2: brak powtarzalności opracowywanych tyflomap [publikacje 3-5].

3. METODYKA BADAWCZA I SCHEMAT POSTĘPOWANIA

W niniejszej rozprawie zaproponowałem autorską metodykę zwiększania potencjału informacyjnego oraz półautomatycznego opracowywania tyflomap tematycznych z wykorzystaniem techniki druku 3D. Metodyka ta obejmuje:

- ocenę wartości informacyjnej tyflomap;
- koncepcję zwiększania wartości informacyjnej tyflomap poprzez wykorzystanie pełnego zakresu zmiennych haptycznych;
- zdefiniowanie etapów opracowywania tyflomap, które mogą zostać zautomatyzowane, dzięki ich standaryzacji i parametryzacji;
- wybór algorytmów i/lub modeli generalizacji danych przestrzennych do poziomu czytelnego przez ONS;
- zasady postępowania przy redagowaniu i reprodukcji tyflomap tematycznych drukowanych w 3D uwzględniający:
    - zastosowanie warstw kotwiczących (anchor layers), wykorzystywanych do budowy mapy podkładowej wspólnej dla wszystkich map tematycznych w atlasie lub serii map;
    - zdefiniowanie wytycznych redakcyjnych i reprodukcyjnych tyflomap;
    - optymalizację wykorzystania zmiennych haptycznych;
    - parametryzację wymiarów znaków tyflokartograficznych, odległości między nimi oraz aspektów związanych z redakcją treści mapy, pod kątem planowanej do wykorzystania technologii druku 3D;
    - parametryzację procesu generalizacji treści dotykowej i graficznej;
    - koncepcję w pełni automatycznych procesów selekcji, wygładzania, wyrównania i przesuwania elementów treści tyflomap.

W swoich pracach przyjąłem trzy hipotezy badawcze:

H1. zasób informacyjny tyflomap można ocenić klasycznymi metodami poprzez wykorzystanie zmiennych haptycznych do wyznaczenia liczby jednostkowych informacji przekazywanych przez znaki tyflokartograficzne [Publikacja 1];

H2. zróżnicowanie wysokości znaków tyflokartograficznych umożliwia redukcję rekomendowanych minimalnych odstępów między nimi i umieszczenie na tyflomapie więcej treści [Publikacja 2];

H3. automatyzacja wybranych etapów opracowywania tyflomap wymaga sprecyzowania sposobu postępowania na poszczególnych etapach opracowania mapy oraz precyzyjnego zdefiniowania parametrów mających wpływ na jej czytelność [Publikacje 3-5].

Zestawienie etapów prac i problemów badawczych wraz z metodami i sposobami ich rozwiązania oraz odniesienia do wyżej wymienionych hipotez przedstawia Tabela 1.

Tabela 1 Metody stosowane na poszczególnych etapach prac badawczych

Lp.	Problem badawczy	Etapy prac badawczych	Odniesienie do publikacji	Odniesienie do hipotezy	Metody i sposoby rozwiązania
1	Niewielka ilość informacji przekazywana za pomocą tyflomap	Zaproponowanie sposobu oceny wartości informacyjnej tyflomap	Publikacja 1	Hipoteza 1	metody kartometrii: strukturalna miara informacji oraz współczynnik wydajności informacyjnej
		Opracowanie koncepcji zwiększania wartości informacyjnej tyflomap poprzez wykorzystanie pełnego zakresu zmiennych haptycznych	Publikacja 1 Publikacja 2	Hipoteza 2	semiotyka (w zakresie relacji semantycznych i syntaktycznych); metoda porównawcza; metoda eksperymentu; metoda sondażu diagnostycznego: techniki ankiet i wywiadu
2	Brak powtarzalności opracowywanych tyflomap	Zdefiniowanie etapów opracowywania tyflomap, które mogą zostać zautomatyzowane, dzięki ich standaryzacji i parametryzacji	Publikacja 3	Hipoteza 3	metoda krytycznej analizy literatury; metoda sondażu diagnostycznego: technika ankiet
		Wybór algorytmów i/lub modeli generalizacji danych przestrzennych do poziomu czytelnego przez ONS	Publikacja 4		metoda systematycznej analizy literatury
		Opracowanie sposobu postępowania przy redagowaniu i reprodukcji tyflomap tematycznych drukowanych w 3D	Publikacja 5		metoda analizy i syntezy; metoda weryfikacji z wykorzystaniem prototypu; metoda sondażu diagnostycznego: techniki ankiet i wywiadu

Opis szczegółowych problemów badawczych składających się na niniejszą rozprawę, metod ich rozwiązania oraz uzyskanych wyników badań stanowi treść kolejnych podrozdziałów. W podrozdziale 4.1. zaproponowałem metodę oceny wartości informacyjnej tyflomap. Podrozdział 4.2. przedstawia metodę zwiększania potencjału informacyjnego poprzez wykorzystanie wszystkich zmiennych haptycznych, przy jednoczesnym zachowaniu czytelności tyflomap. W podrozdziałach 4.3. oraz 4.4. przedstawiłem wyniki badań w formie artykułów przeglądowych. Celem pierwszego artykułu przeglądowego (podrozdział 4.3.) było zidentyfikowanie zestawów rekomendowanych znaków dotykowych do wykorzystania na tyflomapach oraz parametrów związanych z redakcją tyflomap wraz z ich sugerowanymi wartościami, które można modyfikować zależnie od wykorzystanej metody produkcji i planowanego przeznaczenia mapy. Celem drugiego (podrozdział 4.4.) było zidentyfikowanie rozwiązań, które mogą zostać wykorzystane do automatycznego generowania map, w tym tyflomap, z uwzględnieniem procesu generalizacji danych przestrzennych. Podrozdział 4.5. przedstawia metodykę półautomatycznego opracowywania tyflomap tematycznych oraz jej weryfikację z wykorzystaniem prototypu tematycznej tyflomapy hybrydowej.

4. PROBLEMY BADAWCZE, METODY, WYNIKI BADAŃ

4.1. Metoda oceny wartości informacyjnej tyflomap [publikacja 1]

Jak już zostało wspomniane, ze względu na wymagany wysoki poziom generalizacji, treść, którą można zmieścić na jednym arkuszu tyflomapy jest niewielka. Dlatego też ważnym zadaniem jest przekazanie jak najwięcej informacji, wykorzystując jak najmniej elementów na mapie, których nadmiar mógłby powodować nieczytelność. Dotychczasowym problemem był jednak brak metody oceny wartości informacyjnej tyflomap**,** który umożliwiłby oszacowanie, jak modyfikacje procesu redakcyjnego tyflomap wpływają na ilość przekazywanych przez nie informacji. W związku z tym podjąłem się badań nad wypracowaniem metody ilościowej oceny tyflomap pod kątem przekazywanej wartości informacyjnej, rozumianej jako „poziom zaspokojenia potrzeb informacyjnych użytkownika" (Potelarska-Walczyńska, 1979). Starałem się tym samym znaleźć odpowiedzi na dwa pytania badawcze:

1. Czy metody oceny wartości informacyjnej klasycznych map mogą zostać zastosowane do oceny tyflomap?
2. W jaki sposób wykorzystana metoda reprodukcji, a co za tym idzie sposób projektowania znaków, wpływają na wartość informacyjną tyflomap?

Aby odpowiedzieć na pierwsze pytanie badawcze, zidentyfikowałem istniejące metody oceny wartości informacyjnej klasycznych map, a następnie zmodyfikowałem je w taki sposób, żeby możliwe było ich zastosowanie do oceny tyflomap. Zaproponowałem wykorzystanie dwóch miar: strukturalnej miary informacji zaproponowanej przez Saliszczewa (2002) oraz współczynnika wydajności informacyjnej, po raz pierwszy zdefiniowanego przez Grygorenkę (1973). Obie wymienione metody w swojej oryginalnej wersji bazują na zmiennych graficznych – konieczna była zatem ich adaptacja. Zaproponowałem, aby do wyznaczenia ilości informacji przekazywanych za pomocą znaków dotykowych zastosować zmienne haptyczne.

Pierwsza z wymienionych miar – strukturalna miara informacji - wymaga przypisania każdemu znakowi kartograficznemu liczby unikalnych informacji, które przekazuje, i na tej podstawie przypisania im wag. Dla przykładu, znak punktowy na mapie reprezentujący obszar zamieszkany, dostarcza odbiorcy informację na temat położenia tego obszaru, ale może też uwzględniać dodatkowe informacje, takie jak jego populacja czy poziom administracyjny. Liczbę przekazywanych informacji można zwiększać, wykorzystując potencjał zmiennych haptycznych i/lub graficznych. Tym samym znak reprezentujący miasta można różnicować za pomocą barwy lub rozmiaru. W tym przykładzie, miasta o większej populacji mogą być oznaczane większym znakiem, zaś stolice państw wyróżnione inną barwą.

Aby wyznaczyć strukturalną miarę informacji całego arkusza mapy, należy – oprócz liczby przekazywanych przez każdy znak jednostkowych informacji - zliczyć poszczególne rodzaje znaków. O ile w przypadku znaków punktowych zadanie jest łatwe, o tyle dla znaków liniowych i powierzchniowych należy zastosować odpowiednie miary geometryczne: długość znaków liniowych i długość obrysów znaków powierzchniowych, wyrażone w skali mapy. Powyższe prowadzi nas do wzoru na obliczenie strukturalnej miary informacji:

$$SMI_i = \sum_{i=1}^{k} a_i * p_i + \sum_{i=1}^{l} b_i * p_i + \sum_{i=1}^{m} c_i * p_i \quad (1)$$

gdzie: SMI_i to strukturalna miara informacji segmentu mapy *i*; *k,l,m* to liczba typów znaków odpowiednio punktowych, liniowych i powierzchniowych; *a* to liczba znaków punktowych danego typu; *b* to długość znaków liniowych danego typu; *c* to długość obrysów znaków powierzchniowych danego typu; *p* to liczba informacji przypisanych konkretnemu typowi znaku (waga znaku).

Docelowo, aby zsumować obliczone w powyższy sposób miary, wyniki cząstkowe należy znormalizować.

Druga miara – współczynnik wydajności informacyjnej - bazuje na kartograficznych środkach wyrazu, czyli, w przypadku tyflomap, wszystkich elementach haptycznych służących do tworzenia znaków, które nie tylko odróżniają znaki od siebie, ale także wpływają na czytelność mapy. Współczynnik ten obliczany jest według wzoru:

$$W = \frac{i}{z} \quad (2)$$

gdzie: *W* to współczynnik wydajności informacyjnej, *i* to liczba informacji przekazywanych przez wszystkie znaki znajdujące się na mapie, *z* to wszystkie kartograficzne środki wyrazu wykorzystane do stworzenia wszystkich znaków kartograficznych na danej mapie.

Współczynnik ten może zostać obliczony dla całej mapy lub oddzielnie dla każdego znaku na mapie. Jego optymalna wartość powinna wynosić 1 – co znaczyłoby, że każdy kartograficzny środek wyrazu służy do przekazania jednej informacji.

Po zaproponowaniu miar na wyznaczenie wartości informacyjnej, zweryfikowałem ich przydatność do oceny tyflomap wykonanych w różnych technikach druku. W tym celu porównałem dwie mapy przedstawiające to samo zjawisko – krainy geograficzne Polski, ale przygotowane w odmienny sposób. Pierwsza z nich (nazywana dalej mapą z atlasu) to mapa pochodząca z Atlasu do Przyrody (Towarzystwo Opieki nad Ociemniałymi w Laskach, 2010), który jest wykorzystywany w polskich ośrodkach kształcących dzieci niewidome i słabowidzące. Atlas został opracowany z użyciem metody transparentnego druku reliefowego nałożonego na barwny poddruk. Druga mapa wykorzystana w badaniu (nazywana dalej mapą 3D) została opracowana przeze mnie z wykorzystaniem technologii FDM druku 3D (Wabiński & Mościcka, 2017). Przy jej opracowywaniu współpracowałem z tyflopedagogami z Ośrodka Szkolno-Wychowawczego dla Dzieci Niewidomych w Laskach. Obie mapy bazują na dobrych praktykach w zakresie opracowywania tyflomap (np. BANA and the CBA, 2010; Edman, 1992) oraz są zgodne z programem nauczania geografii w szkołach podstawowych, chociaż nieznacznie się różnią, np. zostały opracowane w innych skalach. Różnice te, z uwagi na duży stopień generalizacji treści, nie wpłynęły jednak w istotny sposób na uzyskane wyniki.

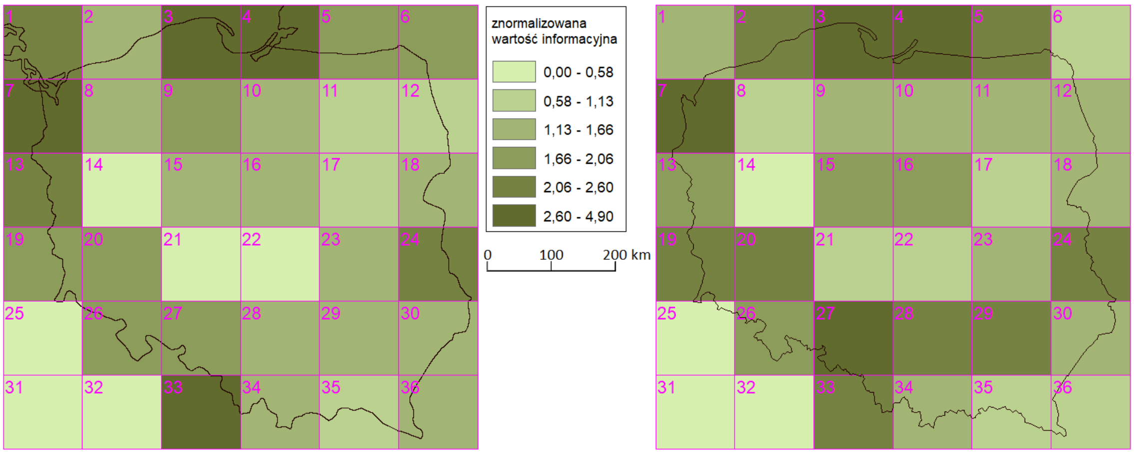
Ze względu na możliwości oferowane przez technikę druku, na mapie 3D wprowadzono modyfikacje, w stosunku do mapy z atlasu. Przede wszystkim, dzięki dowolności w zakresie projektowania znaków, jaką daje druk 3D, zastosowałem różnicowanie wysokości znaków, żeby w ten sposób zwiększyć czytelność mapy. Poza tym, poszczególne krainy geograficzne zostały wyniesione na różną wysokość ponad poziom mapy, bazując na średnich wysokościach nad poziomem morza na tych obszarach.

Obie mapy zostały przetestowane przez ONS i ocenione jako czytelne. Dlatego ani stopień czytelności, ani redakcja kartograficzna nie były przedmiotem badań – skupiłem się tylko na mierzalnych parametrach ilościowych.

Obliczenia dwóch zaproponowanych miar przeprowadziłem na rysunkach wektorowych obydwu map sprowadzonych do tej samej skali. Aby szczegółowo przeanalizować rozkład informacji na każdej z map, zostały one podzielone na równą liczbę segmentów (36), by możliwe było zbadanie rozkładu zagęszczenia treści (wartości informacyjnej) w poszczególnych częściach arkuszy. Dodatkowo, informacje przedstawione na mapach podzieliłem na dwie kategorie: tematyczną (krainy geograficzne) oraz podkładową (granice państw, rzeki, jeziora, wyspy). Strukturalna miara informacji była zatem liczona dla każdego segmentu mapy oddzielnie, osobno dla treści tematycznej i podkładowej. Wyniki wyznaczonej wartości strukturalnej miary informacji przedstawia Tabela 2, zaś ich rozkład na mapach pokazuje Rys. 2.

Tabela 2 Strukturalna miara informacji z podziałem na treść tematyczną i podkładową.

	MAPA Z ATLASU	MAPA 3D
CAŁY ARKUSZ MAPY	54.15	61.68
TREŚĆ TEMATYCZNA	18.69 (35%)	32.70 (53%)
TREŚĆ PODKŁADOWA	35.46 (65%)	28.98 (47%)



Rys. 1. Rozkład wartości strukturalnej miary informacji w segmentach mapy.
Po lewej stronie mapa z atlasu, po prawej stronie mapa 3D.

Współczynnik wydajności informacyjnej wyniósł dla mapy z atlasu 0,79; natomiast dla mapy 3D: 0,95; co jest wartością zbliżoną do wartości optymalnej - 1. Wartości te oraz wyniki przedstawione w Tabeli 2 pokazują, że zastosowanie techniki druku 3D umożliwia zwiększenie wartości informacyjnej tyflomap o co najmniej kilkanaście procent, co stanowi odpowiedź na drugie pytanie badawcze.

Wyniki analiz przyniosły odpowiedź na pierwsze pytanie badawcze i potwierdziły, że możliwe jest zastosowanie klasycznych metod obliczania wartości informacyjnej do oceny tyflomap. Ponadto, wykorzystanie potencjału dodatkowej zmiennej haptycznej, czyli zróżnicowanie wysokości poszczególnych znaków w przypadku mapy 3D, umożliwia zwiększenie wartości informacyjnej mapy, bez negatywnego wpływu na jej czytelność.

Badania przedstawione w publikacji 1 umożliwiły osiągnięcie celu szczegółowego a) i przyczyniły się do realizacji celu głównego 1).

4.2. Koncepcja zwiększania wartości informacyjnej tyflomap [publikacja 2]

Przedstawiona w publikacji 1 metoda oceny wartości informacyjnej tyflomap umożliwia porównywanie ilości informacji przekazywanych za pomocą różnych map. Jest to istotne w obliczu **problemu niewielkiej wartości informacyjnej tyflomap** i potrzebą oceny, czy proponowane nowe rozwiązania z zakresu redakcji tyflomap zwiększają ilość przekazywanych informacji. Wnioski płynące z badań przedstawionych w publikacji 1 pokazały, że potencjał informacyjny zmiennych haptycznych nie był dotychczas w pełni wykorzystywany, głównie z uwagi na ograniczenia stosowanych technik druku w zakresie projektowania znaków tyflokartograficznych. Problem ten eliminuje między innymi technika druku 3D, która umożliwia praktycznie pełną dowolność w zakresie drukowania zaprojektowanych znaków.

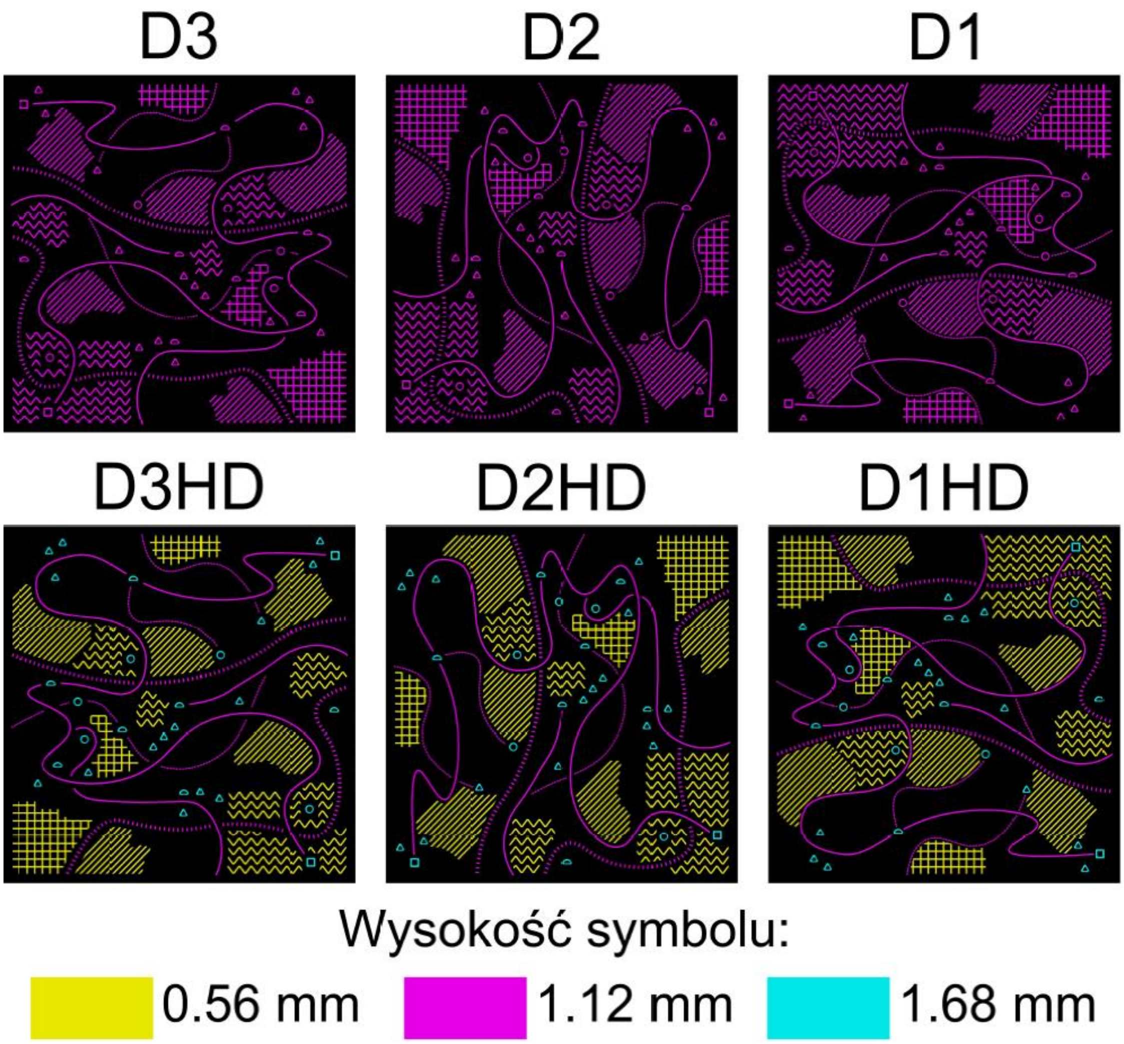
Podjąłem zatem badania nad sprawdzeniem, czy wynoszenie znaków na tyflomapach na różne wysokości, umożliwia redukcję minimalnych, sugerowanych w literaturze, poziomych odstępów między znakami, bez negatywnego wpływu na czytelność mapy. Potwierdzenie tej hipotezy umożliwiłoby przygotowywanie map w mniejszych skalach, redukując tym samym koszty ich produkcji, lub na umieszczenie na mapach dodatkowych informacji, które nie mogłyby się na nich zmieścić bez zmniejszenia tych odstępów. Tym samym możliwe byłoby zwiększanie ilości informacji zamieszczanych na tyflomapach.

Podczas badań poszukiwałem odpowiedzi na następujące pytania badawcze:

1. Czy różnicowanie wysokości znaków kartograficznych na tyflomapach umożliwia redukcję rekomendowanych minimalnych odstępów między nimi?
2. Do jakiego stopnia możliwe jest zredukowanie tych odstępów, o ile w ogóle?
3. Czy zmniejszenie odstępów między znakami zwiększa wartość informacyjną tyflomap?

W ramach badań zaprojektowałem zestaw sześciu pseudomap (Nolan & Morris, 1971), które nie bazują na konkretnych danych przestrzennych, ale zostały specjalnie opracowane na potrzeby niniejszego badania. Pseudomapy zostały zaprojektowane tak, aby możliwe było przeprowadzanie na ich podstawie prostych zadań lokalizacyjnych i zweryfikowanie przez ONS postawionej hipotezy. Opracowane pseudomapy różniły się między sobą minimalnymi poziomymi odstępami między znakami: 3 mm jako wartość referencyjna, sugerowana w literaturze przedmiotu (BANA and the CBA, 2010; Nolan & Morris, 1971; Więckowska et al., 2012) oraz zaproponowane przeze mnie warianty z odstępami 2 mm i 1 mm. Każdy z wariantów został przygotowany w dwóch wersjach: bez i z zastosowaniem różnicowania wysokości znaków. Stopień wyniesienia poszczególnych rodzajów znaków ponad poziom mapy bazuje na wytycznych z literatury (Wabiński & Mościcka, 2017; Wiedel & Groves, 1969), według zasady: im mniejszy znak, tym wyżej powinien być wyniesiony. Zaprojektowane znaki powierzchniowe miały wysokość 0,56 mm, liniowe 1,12 mm, a punktowe 1,68 mm.

Warianty bez różnicowania wysokości (oznaczone jako D1, D2, D3 na Rys. 3.) posłużyły do zweryfikowania wpływu minimalnych odstępów na czytelność tyflomap i stanowiły odniesienie dla wariantów z zastosowanym różnicowaniem wysokości (D1HD, D2HD, D3HD na Rys. 3.).



Rys. 2. Warianty pseduomap wykorzystane w badaniu.
Kolory symbolizują różny stopień wyniesienia znaków ponad poziom arkusza mapy.

Aby zredukować wpływ potencjalnych zmiennych zakłócających, przygotowałem łącznie siedem wariantów rozmieszczenia znaków na pseudomapach, poprzez zastosowanie obrotów i lustrzanych odbić elementów treści. Sześć z nich to przedstawione na Rys. 3. warianty, na których były realizowane zadania lokalizacyjne. Dodatkowy wariant to pseudomapa pilotażowa, która służyła do zapoznania się ze znakami i legendą. Dzięki takiemu podejściu uniknąłem sytuacji, w której uczestnicy badań mogliby nauczyć się na pamięć rozmieszczenia znaków na pseudomapach, a jednocześnie nie wpłynąłem na ogólną liczbę znaków na każdej nich. Poszczególne warianty były przedstawiane uczestnikom badań w losowej kolejności. Wszystkie pseudomapy zostały wydrukowane w technologii FDM druku 3D.

Pseudomapy wykorzystane w badaniu przedstawiały lokalizację skarbu. Zastosowane na mapie znaki zostały starannie wyselekcjonowane na podstawie dobrych praktyk w zakresie projektowania znaków dotykowych oraz moich poprzednich doświadczeń z tyflomapami drukowanymi w 3D. Wybrałem zestaw łatwo rozróżnialnych znaków, które w przeszłości były stosowane na tyflomapach drukowanych w 3D.

W celu weryfikacji postawionej w badaniu hipotezy, przeprowadziłem kontrolowane sesje badawcze z udziałem 30 ONS, zarówno niewidomych od urodzenia, jak i ociemniałych. Grupa badawcza została wybrana spośród zgłoszonych kandydatów w taki sposób, aby jak najbardziej zróżnicować uczestników badania, między innymi ze względu na wiek, płeć i doświadczenie w pracy z tyflomapami. Każdy uczestnik badania miał do wykonania trzy zadania, które musiał powtórzyć na każdym z sześciu wariantów pseudomapy. Notowana była poprawność i czas wykonywania zadań. Na tej podstawie możliwa była ocena poszczególnych wariantów. Zadania polegały na:

1. wskazaniu 5 znaków punktowych danego typu;
2. zlokalizowaniu 5 znaków powierzchniowych;
3. podążaniu po ścieżce (znaku liniowym) od wskazanej przez prowadzącego badanie lokalizacji, do miejsca ukrycia skarbu.

Jak pokazały wyniki, w przypadku zadania nr 1, warianty mapy z zastosowanym różnicowaniem wysokości charakteryzowały się średnio zdecydowanie krótszymi czasami wykonania zadań (110 s) oraz mniejszą liczbą zadań, które nie zostały wykonane w ustalonym limicie 5 minut (1), niż te bez różnicowania wysokości znaków: średnio 20 niewykonanych zadań, a w przypadku pozostałych przeciętnie 173 sekundy potrzebne na ich wykonanie. Co ciekawe, w przypadku wariantów z zastosowanym różnicowaniem wysokości znaków, wyniki były bardzo podobne między sobą, niezależnie od minimalnych odstępów między znakami (Tabela 3). Porównywalne wyniki uzyskano dla zadania nr 3, chociaż ogólna liczba zadań niewykonanych była niższa, podobnie jak średnie czasy wykonania pozostałych. W tym jednak przypadku dało się zaobserwować znaczne pogorszenie czytelności w przypadku wariantu bez różnicowania wysokości znaków i zredukowanymi do 1 mm odstępami między nimi (Tabela 3). Zadanie nr 2 okazało się być łatwym, niezależnie od wariantu mapy. Wynika to prawdopodobnie z łatwości identyfikacji dużych znaków powierzchniowych na pseudomapach (Tabela 3).

Tabela 3 Statystki zadań lokalizacyjnych.

KOD WARIANTU MAPY	D1	D2	D3	D1HD	D2HD	D3HD
ZADANIE NR 1						
LICZBA BŁĘDÓW	28	19	13	1	1	1
ŚREDNI CZAS	02:45	03:12	02:41	01:43	01:40	02:07
ZADANIE NR 2						
LICZBA BŁĘDÓW	0	0	0	0	0	0
ŚREDNI CZAS	00:27	00:21	00:22	00:28	00:22	00:24
ZADANIE NR 3						
LICZBA BŁĘDÓW	23	0	0	0	0	0
ŚREDNI CZAS	02:40	01:04	00:47	00:42	00:41	00:29

Z punktu widzenia dwóch pierwszych pytań badawczych, parą wariantów, którą chciałem przede wszystkim porównywać były: D3 jako wariant opracowany zgodnie z obowiązującymi wytycznymi oraz D1HD jako wariant z zaproponowanymi przeze mnie modyfikacjami. Przedstawione wyniki potwierdzają, że możliwe jest zredukowanie odstępów poziomych między znakami nawet do 1 milimetra, pod warunkiem, że będzie występowało różnicowanie wysokości znaków na tyflomapie. Powyższe stanowi bezpośrednie odpowiedzi na pierwsze i drugie pytanie badawcze. Nie tylko nie wpływa to negatywnie na czytelność tyflomap, ale wręcz poprawia odbiór tak zaprojektowanych map dotykowych.

W trakcie sesji badawczych, każdy z uczestników został poproszony o wypełnienie kwestionariusza, który stanowił podstawę analizy jakościowej badań. Szczególnie interesował mnie ogólny poziom zrozumienia prezentowanych wariantów map oraz to, jak sprawował się materiał użyty do produkcji map pod względem komfortu dotykowego. Zdecydowana większość uczestników badań na pytanie: „Czy korzystanie z tyflomap było komfortowe?", odpowiedziało „zdecydowanie tak" lub „tak" (ponad 93%). W przypadku pytania: „Czy łatwo było zrozumieć prezentowane w trakcie badania materiały dotykowe?”, jedna trzecia ankietowanych odpowiedziała „zdecydowanie tak”, natomiast ponad połowa – „tak”, co daje łącznie blisko 87% pozytywnych ocen.

Sesje badawcze przeprowadzane z udziałem ONS były także źródłem sugestii usprawnień, pochodzących od bezpośrednio zainteresowanych, którzy sami najlepiej identyfikują własne potrzeby (Stangl & Yeh, 2015). Dowiedziałem się między innymi, które znaki spośród wybranych były najbardziej czytelne, a które wymagają modyfikacji. Dla niektórych uczestników badania mylące było to, że znaki użyte na pseudomapach mają inne znaczenia na innych znanych im tyflomapach. Stanowi to praktyczne potwierdzenie wspomnianego w dalszej części autoreferatu problemu „lokalnej standaryzacji” (porównaj Rozdział 4.3.). Część ankietowanych zwróciła również uwagę na zbyt silnie zaokrąglanie niektórych znaków, co prowadziło do mylenia kwadratu z okręgiem. Zaokrąglenia zastosowałem dla podniesienia komfortu dotykowego, który został wysoko oceniony. Jest to więc kwestia kompromisu między czytelnością a komfortem.

Trzecie postawione pytanie badawcze dotyczyło wartości informacyjnej tyflomap. Wykorzystując metody opisane w Rozdziale 4.1., zweryfikowałem wpływ redukcji odstępów między znakami na wartość informacyjną opracowanych pseudomap. Ze względu na jednakową liczbę znaków punktowych na każdym opracowanym wariancie, uwzględniłem w obliczeniach tylko długość znaków liniowych i długość obrysów znaków powierzchniowych. Okazało się, że średnie przyrosty wartości informacyjnej wyniosły 3,5% oraz 6,9% przy zmniejszeniu minimalnych odstępów odpowiednio do 2 i 1 mm. Jest to istotny wzrost, jeśli weźmiemy pod uwagę koszty produkcji tyflomap oraz stopień skomplikowania ich generalizacji.

Podsumowując, różnicowanie wysokości znaków na tyflomapach umożliwia nie tylko szybsze rozwiązywanie zadań lokalizacyjnych, co świadczy o dobrej czytelności map, ale też zostało ocenione jako rozwiązanie podnoszące komfort korzystania z tyflomap. Umożliwia także redukcję minimalnych odstępów między znakami, co z kolei przekłada się na wzrost wartości informacyjnej.

Badania przedstawione w publikacji 2 umożliwiły osiągnięcie celów szczegółowych b) oraz przyczyniły się do realizacji celów głównych 1).

4.3. Wybór etapów i parametrów opracowywania tyflomap, które mogą zostać jednoznacznie zdefiniowane [publikacja 3]

Redukcja czasu i kosztów opracowywania tyflomap, a także zagwarantowanie powtarzalności tego procesu, wymagają ustandaryzowanej procedury, która bazuje na jednoznacznych zasadach i wytycznych dotyczących ich projektowania. Procedura ta ma na celu ujednolicenie zasad przygotowania map w taki sposób, aby jakość map obejmujących ten sam temat i obszar była równoważna, czyli niezależna od subiektywnych rozwiązań autorów. Niezbędne jest zatem zdefiniowanie wytycznych obejmujących zasady postępowania przy opracowywaniu tyflomap, optymalne kryteria dotyczące generalizacji oraz sposób projektowania znaków tyflokartograficznych i mierzalne parametry związane z redakcją map, które obniżyłyby poziom subiektywności końcowego wyniku.

Celem badań było zidentyfikowanie etapów i parametrów związanych z opracowywaniem tyflomap, które mogą być precyzyjnie zdefiniowane, w celu ujednolicenia sposobu ich przygotowywania. W związku z tym realizację prac badawczych rozpocząłem od przeglądu literatury oraz dobrych praktyk, podsumowując dotychczasową wiedzę na temat tego, jak należy projektować tyflomapy. W trakcie prac starałem się odpowiedzieć na trzy główne pytania badawcze:

4. Jakie są rekomendacje dotyczące projektowania znaków na tyflomapach?
5. Jakie są rekomendowane zestawy znaków tyflokartograficznych?
6. Jakie parametry generalizacyjne (i ich wartości) mogą zostać zdefiniowane na potrzeby tyflokartografii?

Podstawowym założeniem badań było to, że wszechstronna wiedza na temat opracowywania tyflomap wymaga zarówno wiedzy naukowej, jak i praktycznej. Ta pierwsza jest zazwyczaj rozpowszechniana w recenzowanych publikacjach naukowych i łatwo dostępna. Wiedza praktyczna to głównie dobre praktyki stosowane przez osoby zajmujące się opracowywaniem tyflomap. Jest ona trudniej dostępna, bo rzadko kiedy sformalizowana i rozpowszechniana w języku angielskim - pochodzi z mniej oficjalnych wytycznych, często znanych tylko lokalnie. W swoich badaniach, do rozwiązania postawionego problemu badawczego, wykorzystałem obydwa wymienione źródła informacji.

W ramach badań przeanalizowałem literaturę naukową, obejmującą kilkaset pozycji, pochodzących głównie z moich prywatnych repozytoriów, zgromadzonych w ramach wstępnych prac badawczych. Analizując źródła bibliograficzne, wykorzystałem także wsteczne przeszukiwanie (backward reference search) oraz przeprowadzony przeze mnie systematyczny przegląd literatury dotyczący generalizacji i automatyzacji opracowywania map (Wabiński & Mościcka, 2019). Przeszukałem również wybrane bazy danych, m. in. Scopus i Web of Science, wykorzystując słowa kluczowe, takie jak: „tactile maps guidelines", „automatic map generalization".

W związku z faktem, że lokalnie wykorzystywane dobre praktyki i mniej formalne wytyczne rzadko kiedy są publikowane w międzynarodowych czasopismach, przygotowałem kwestionariusz, który rozesłałem do osób zajmujących się tyflokartografią na całym świecie, korzystając z listy adresowej jednej z komisji Międzynarodowej Asocjacji Kartograficznej (ICA) - Commission on Maps and Graphics for Blind and Partially Sighted. Kwestionariusz zawierał 20 pytań, które dotyczyły między innymi wykorzystywanych w danych krajach metod reprodukcji tyflomap oraz istnienia wytycznych lub udokumentowanych dobrych praktyk ich projektowania. Uzyskałem 8 odpowiedzi z 7 różnych krajów: Brazylii, Iraku, Kanady, Meksyku, Polski, Stanów Zjednoczonych i Wielkiej Brytanii, dzięki czemu udało się zidentyfikować wytyczne, do których stosują się tyflokartografowie w wybranych krajach, a które nie są powszechnie dostępne.

Z przeglądu literatury i dobrych praktyk wynika, że wiele zostało już zrobione w kontekście standaryzacji kluczowych etapów procesu opracowywania tyflomap. W literaturze można znaleźć jednoznaczne zasady i mierzalne parametry związane z symbolizacją, generalizacją i redakcją tyflomap. Wiele z najbardziej użytecznych i jednoznacznych reguł pochodzi z mniej oficjalnych wytycznych, opartych na praktycznej wiedzy ich twórców, a same reguły i propozycje zostały często eksperymentalnie zweryfikowane przez ONS.

W wyniku przeglądu literatury wybrałem etapy opracowywania tyflomap, i parametry z nimi związane, które mogą zostać zdefiniowane w celu jego ujednolicenia. Są to przede wszystkim rekomendacje dotyczące projektowania znaków tyflokartograficznych. Zalecenia te dotyczą zarówno ich cech geometrycznych, jak i propozycji konkretnych przykładów znaków dotykowych.

Analizując zalecenia dotyczące cech geometrycznych znaków, każdy ich rodzaj na mapach (punktowe, liniowe, powierzchniowe, napisy) rozpatrzyłem oddzielnie.

Podstawowym zaleceniem jest, podobnie jak w przypadku map klasycznych, by kształt znaków kojarzył się z mapowanym obiektem, ale jednocześnie był możliwie jak najprostszy, ponieważ prostota jest uważana za drugą najważniejszą zasadę po czytelności w projektowaniu tyflomap (Nolan & Morris, 1971). Jako znaki punktowe należy stosować proste kształty geometryczne, takie jak koło, trójkąt, prostokąt czy kwadrat (Bris, 2001; ISO, 2019; Polak i Olczyk, 2010). Możliwe jest uzupełnienie tego zbioru o symbole krzyżyka, plusa lub gwiazdki (The N.S.W. Tactual and Bold Print Mapping Committee, 2006). Zalecane jest stosowanie pojedynczych linii, ponieważ umożliwiają one szybszą eksplorację mapy i lepsze zapamiętywanie treści (Bentzen i Peck, 1979; Easton i Bentzen, 1980). Znaki powierzchniowe są charakteryzowane trójnasób: poprzez styl (kształt elementów tworzących teksturę), natężenie (odległość między tymi elementami) oraz grubość (szerokość elementów), które można w łatwy sposób parametryzować (The N.S.W. Tactual and Bold Print Mapping Committee, 2006). Poszczególne tekstury powinny się różnić przynajmniej dwoma parametrami, np. kształtem elementów tworzących teksturę oraz odstępami między nimi. Jeśli chodzi o napisy na mapach, to etykiety brajlowskie powinny być zorientowane poziomo, z wyjątkiem tych opisujących ulice (Edman, 1992; ISO, 2016). Przytoczone wyżej przykładowe rekomendacje dotyczące cech geometrycznych znaków stanowią odpowiedź na postawione przeze mnie pierwsze pytanie badawcze.

Oprócz wytycznych dotyczących cech geometrycznych znaków, przeanalizowałem także zestawy rekomendowanych znaków dotykowych, które we wcześniejszych badaniach uznano za łatwo rozróżnialne w testach z udziałem ONS. Niektóre źródła zalecają zestawy konkretnych znaków wraz z, jeśli ma to zastosowanie, ich znaczeniem i dedykowaną techniką produkcji (BANA and the CBA, 2010; Nolan & Morris, 1971). Choć nie wszystkie źródła podają tak szczegółowe informacje, wiele znaków można uznać za inspirację do indywidualnych eksperymentów i dalszych modyfikacji (ISO, 2016; Regis & Nogueira, 2013). W publikacji zestawiłem zbiory rekomendowanych znaków, odpowiadając tym samym na drugie pytanie badawcze.

Poszukując odpowiedzi na trzecie pytanie badawcze, zdefiniowałem parametry liczbowe związane z opracowywaniem treści mapy, które mogą być jednoznacznie określone. Parametry te dotyczą dwóch głównych grup: wymiarów znaków i odległości między nimi. W przypadku niektórych wartości, istnieją duże rozbieżności w rekomendacjach, w zależności od cytowanego źródła. Na przykład, rekomendowana minimalna wielkość znaku punktowego powinna wynosić od 3-5 mm (Więckowska i in., 2012), do nawet 13 mm (Regis & Nogueira, 2013). Zalecane odległości pomiędzy różnymi znakami wahają się od 1 mm (Wabiński i in., 2022) do nawet 5 mm (Więckowska i in., 2012). Minimalne zalecane odległości pomiędzy znakami i ich adnotacjami wynoszą od 3-4 mm (Więckowska i in 2012) do 3-6 mm (BANA i CBA, 2010r). Jeśli zaś chodzi o rekomendowane wysokości znaków, to minimalna wysokość powinna wynosić 0,2 mm według Jehoela i in. (2006), ale 0,75 mm według Jesenskiego (1988), zaś minimalna różnica wysokości między znakami: 0,04-0,08 mm według Jehoela i in. (2009), ale 0,5 mm wg Brisa (2001).

W wyniku przeglądu literatury i dobrych praktyk wybrałem także etapy opracowywania tyflomap, które mogą być ujęte w ogólne zasady edycji i redakcji tyflomap. Zasady te dotyczą kompozycji mapy jako całości, np. rekomendowane wymiary arkusza tyflomapy, czy format legendy; ale są to również zasady charakterystyczne dla map dotykowych, takie jak wymagania dotyczące ich trwałości i mobilności, np. wypukły trójkąt w prawym górnym rogu mapy służący jako znak orientacji (Więckowska et al., 2012). Zasady edycji obejmują zarówno ogólne reguły implementacji, jak i związane z nimi parametry liczbowe, w tym, np. dopuszczalną liczbę rodzajów znaków kartograficznych na tyflomapach - do 15 (Rowell & Ungar, 2003), w tym nie więcej niż 4 (Červenka, Hanouskov, Másilko, & Nečas, 2013; Więckowska et al., 2012) do 6 rodzajów znaków powierzchniowych (Jesús Villalpando Esparza, 2014).

Podczas badań zidentyfikowałem również szereg przeszkód stojących na drodze do standaryzacji procesu opracowywania tyflomap. Po pierwsze, przytaczane w literaturze wartości parametrów różnią się znacznie w zależności od cytowanego źródła. Rozbieżności te wynikają prawdopodobnie z faktu, że cytowane źródła rzadko kiedy podają wprost, dla jakich technik reprodukcji powinno się stosować opisywane wartości. Prowadzi to do wniosku, że nawet przestrzegając ustandaryzowanej metodyki projektowania, z wykorzystaniem jednoznacznie zdefiniowanych parametrów, ostateczny rezultat w postaci opracowanej mapy, może się różnić. Ponadto, nie wszystkie kształty znaków można odtworzyć, wykorzystując dowolną technikę druku. Tym samym, niezmiernie istotne jest, aby formułując wytyczne podawać dla jakiej metody reprodukcji podawane parametry znajdują zastosowanie.

Kolejnym problemem, jaki zidentyfikowałem w trakcie badań była „lokalna standaryzacja”. Niektóre projekty znaków na tyflomapach są silnie zakorzenione w poszczególnych krajach lub regionach i jednoznacznie kojarzą się z przedstawianym zjawiskiem. Te same znaki mogą jednak mieć zupełnie inne znaczenie w różnych częściach świata. Potrzebne są zatem globalne standardy, takie jakie istnieją w klasycznej kartografii. Dla przykładu - nie podlega dyskusji, że woda na mapach topograficznych powinna być przedstawiana kolorem niebieskim. Ale już na tyflomapach morza i oceany mogą być przedstawiane na różne sposoby: w Polsce za pomocą tekstury składającej się z poziomych linii ciągłych, w Australii za pomocą poziomych linii przerywanych, a w Stanach Zjednoczonych w formie linii ukośnych.

Podsumowując, przeprowadzony przegląd literatury i dobrych praktyk umożliwił stwierdzenie, że mimo iż przez lata powstało wiele przydatnych wytycznych i parametrów dotyczących projektowania tyflomap, to nadal istnieją luki, które uniemożliwiają przygotowanie holistycznej i znormalizowanej procedury ich opracowywania. Ponadto, wiele z istniejących wytycznych pozostaje nieznanych szerszej społeczności, ze względu na niewystarczające ich upowszechnianie.

W obliczu przytoczonych ograniczeń, cytowane dotychczas wytyczne i parametry należy traktować jako wartości sugerowane, które powinny zostać doprecyzowane eksperymentalnie dla danej techniki druku i przetestowane z udziałem osób bezpośrednio zainteresowanych.

Badania przedstawione w publikacji 3 przyczyniły się do realizacji celu głównego 2) oraz osiągnięcia celu szczegółowego c).

4.4. Identyfikacja rozwiązań, które mogą zostać wykorzystane do generalizacji danych przestrzennych oraz automatyzacji procesu opracowywania tyflomap [publikacja 4]

Wypracowanie ujednoliconych zasad redagowania tyflomap powinno obejmować także jedno z największych wyzwań w procesie ich opracowywania, czyli uogólnienie treści do poziomu, który umożliwi jej percepcję przez ONS. Wiąże się to z jednym z najtrudniejszych zagadnień kartografii, czyli generalizacją.

Generalizację w klasycznej kartografii przeprowadza się zazwyczaj przy przechodzeniu ze skali większej do mniejszej. Niekiedy potrzeba generalizacji wynika też z chęci uwypuklenia pewnych cech kartowanego obszaru, np. przy tworzeniu map tematycznych. W przypadku tyflomap, generalizacja jest nieodzowna, niezależnie od tego, czy wykonywana jest transkrypcja map klasycznych do formy dotykowej, czy też kartowanie źródłowych danych przestrzennych (Cole, 2021; Wiedel & Groves, 1969).

Sam proces generalizacji map jest bardzo skomplikowany i dlatego czasochłonny oraz kosztowny. Celem wielu badań jest jego automatyzacja. Automatyczne opracowywanie map klasycznych jest bardzo skomplikowane, ale ze względu na ograniczenia percepcyjne ONS, komplikuje się ono jeszcze bardziej w przypadku tyflomap. W swoich badaniach założyłem, że automatyzacja procesu generalizacji treści na potrzeby tyflomap znacznie usprawniłaby proces redakcji map dotykowych, w tym przede wszystkim zmniejszyła czas niezbędny do przygotowywania, ale także umożliwiła bardziej obiektywną redakcję tyflomap.

Celem badań było zidentyfikowanie i analiza rozwiązań w zakresie automatyzacji opracowywania map oraz koncepcji generalizacji danych, które mogą zostać wykorzystane do automatyzacji procesu redakcji tyflomap. W związku z tym przeprowadziłem systematyczny przegląd literatury, zgodnie z powszechnie przyjętą metodyką w tym zakresie (Kitchenham & Charters, 2007), według przygotowanego uprzednio protokołu badawczego. W ramach przeglądu przeanalizowałem ponad 500 źródeł opublikowanych w latach 2008-2019, szukając odpowiedzi na postawione pytania badawcze:

1. Jakie są istniejące metody i modele generalizacji do automatycznego generowania map tematycznych, podkładowych oraz tyflomap?
2. Jakie są istniejące systemy i rozwiązania w zakresie automatycznego generowania map?
3. Jak zaprojektować bazę danych przestrzennych na potrzeby automatycznego generowania map?

Wyniki badań pokazały, że mimo wielu istniejących i stale powstających algorytmów oraz modeli generalizacyjnych, nie istnieje holistyczne rozwiązanie problemu generalizacji w kartografii. Istnieje natomiast szereg badań prezentujących częściowe rozwiązania poszczególnych zagadnień z tego zakresu.

Poszukując odpowiedzi na pierwsze pytanie badawcze, wykonałem zestawienie algorytmów i modeli generalizacyjnych wraz z opisem ich zastosowania i metodami ewaluacji. Wiele z cytowanych rozwiązań bazuje na systemach agentowych, np. do generalizacji danych batymetrycznych (Yan, Guilbert, & Saux, 2017), obszarów zabudowanych (Neun, Burghardt, & Weibel, 2009), czy też do odtwarzania wyników manualnej generalizacji (Touya, Christophe, Favreau, & Rhaiem, 2018). Wśród najczęściej wymienianych algorytmów generalizacyjnych znalazły się te upraszczające obiekty liniowe, np. Douglas-Peucker, Visalingham-Whyatt (Kazemi, Lim, & Paik, 2009; van Oosterom, Meijers, & Stoter, 2014) oraz je wygładzające, np. Gaussian Line Smoothing, Spline Interpolation (Mackaness, Burghardt, & Duchêne, 2017; Reimer, 2015). Oprócz tego, zidentyfikowałem algorytmy do zarządzania konfliktami graficznymi (Duchêne et al., 2014), transformacji obiektów powierzchniowych na liniowe (Dimov, Palomar, & Ruiz, 2014), czy też do tworzenia skróconych etykiet obiektów w piśmie brajla (Štampach & Mulíčková, 2016).

Według niektórych z badaczy, nie są nam jednak potrzebne nowe algorytmy, a raczej metodyka, która umożliwi ich połączenie i dzięki temu wykorzystanie ich pełnego potencjału (Touya & Duchêne, 2011).

Podczas prac sprawdziłem również, które operatory generalizacyjne pojawiają się najczęściej w analizowanych źródłach. Ustaliłem, że najczęściej wykorzystywanymi w zadaniach generalizacyjnych operatorami były: przewiększenie, przesunięcie, uproszczenie i scalenie. Odpowiednio parametryzując i hierarchizując tego typu operatory generalizacyjne oraz uzależniając procedurę od kontekstu zastosowania, możliwe jest opracowanie metodyki automatycznej generalizacji map (Foerster, Stoter, & Kraak, 2013).

Starając się udzielić odpowiedzi na drugie pytanie badawcze ustaliłem, że większość istniejących rozwiązań z zakresu automatycznego generowania map jest opracowywana przez krajowe agencje mapowe na potrzeby generowania map topograficznych w różnych skalach. Natomiast w zakresie tyflomap istnieją głównie rozwiązania służące automatycznemu generowaniu map do orientacji, które wykorzystywane są przez ONS do planowania tras, nawigacji w terenie oraz lokalizowaniu obiektów fizycznych.

Organy odpowiedzialne za przygotowywanie map w różnych krajach z powodzeniem zaimplementowały metodyki automatycznego opracowywania map, głównie topograficznych, na podstawie wielkoskalowych baz danych przestrzennych, np. w Holandii (Stoter, Post, Van Altena, Nijhuis, & Bruns, 2014) czy w Niemczech (Schürer & Gerhardt, 2010). W swoim badaniu zidentyfikowałem także systemy do automatycznego generowania map pokrycia terenu (Thiemann & Sester, 2018), służących nawigacji (Kopf, Agrawala, Bargeron, Salesin, & Cohen, 2010), jak również map dla turystów (Grabler, Agrawala, Sumner, & Pauly, 2008).

Większość zidentyfikowanych w ramach przeglądu rozwiązań do automatycznego generowania tyflomap pochodziło ze źródeł opublikowanych po 2014 roku. To sygnał, że w ostatnich latach tego typu rozwiązania zyskiwały na popularności. Analizowane systemy bazowały głównie na nieprzetworzonych danych Open Street Map (Götzelmann, 2018; Hänßgen, Waldt, & Weber, 2016; Taylor, Dey, Siewiorek, & Smailagic, 2016). Twórcy tych platform zapomnieli jednak o konieczności odpowiedniej adaptacji wykorzystywanych danych przestrzennych. Samo nadanie symbolizacji i przygotowanie gotowych do druku modeli nie wystarczy - dane muszą być najpierw uproszczone do formy czytelnej przez ONS. Wyróżniającym się na tym tle rozwiązaniem jest zaproponowany przez czeskich badaczy system do automatycznego generowania prostych map topograficznych w różnych skalach, gotowych do wydruku na papierze puchnącym (Červenka, Břinda, Hanousková, Hofman, & Seifert, 2016).

Niestety, wiele ze zidentyfikowanych w ramach badania rozwiązań przestało być rozwijanych. Powodem może być brak finansowania, ale również to, że platformy te okazały się w rzeczywistości nieprzydatne, chociaż w warunkach laboratoryjnych spełniały swoje zadanie. Potwierdza to wniosek z pracy Brulé i in. (2020), że badacze często zapominają o odpowiedniej ewaluacji swoich prac w środowisku ONS.

Sformułowanie odpowiedzi na trzecie pytanie badawcze było trudne. Większość analizowanych w ramach badania źródeł dostarczała niewiele informacji na ten temat, co wynika prawdopodobnie z faktu, że specyfikacje baz danych przestrzennych do automatycznego generowania map są albo tajne, albo opisane w dokumentacjach technicznych, które nie stanowią części publikacji naukowych.

Mimo to, zidentyfikowałem źródła, które umożliwiają odpowiedź na trzecie pytanie badawcze. Robocza metodyka przejścia od surowych danych przestrzennych do ich końcowej wizualizacji w różnych skalach została zaproponowana przez Šuba (2017). Struktury baz danych krajowych organów odpowiedzialnych za zarządzanie danymi przestrzennymi zostały opisane w pracy Foerster i in. (2013). Częstym rozwiązaniem jest opracowanie bazy głównej (master database), przechowującej dane o najwyższej dokładności, z których generowane są produkty zgeneralizowane (Benz & Weibel, 2014). Istnieją dwa główne podejścia w generowaniu takich produktów z bazy głównej: wykorzystujące strukturę gwiazdy (star), gdzie każdy produkt jest generowany bezpośrednio z bazy głównej; oraz drabiny (ladder), w którym z bazy głównej generowany jest produkt o niskim stopniu generalizacji, z którego generuje się kolejne przybliżenia. Większość krajowych agencji mapowych w Europie wykorzystuje podejście mieszane (Duchêne et al., 2014).

Niezależnie od wykorzystywanego podejścia, bazy danych przestrzennych do automatycznego generowania map powinny być zasilane dokładnymi i aktualnymi danymi. Najlepiej, gdyby to były dane darmowe i publicznie dostępne. Baza główna powinna również umożliwiać ujednolicenie danych pochodzących z różnych źródeł (Ducasse et al., 2015).

Spełnienie wszystkich powyższych warunków jest niezmiernie trudne. Dlatego też alternatywnie, podobnie jak w przypadku algorytmów generalizacyjnych, zamiast opracowywać zupełnie nowe repozytorium danych, można wykorzystać te już istniejące, zwłaszcza, że wiele cytowanych rozwiązań bazuje na takich właśnie zbiorach, np. Open Street Map (OpenStreetMap Foundation, 2022). Należy jednak pamiętać o właściwej adaptacji tych danych na potrzeby percepcyjne ONS.

Przeprowadzony przegląd literatury umożliwił ponadto zidentyfikowanie istniejących luk w zakresie automatycznego opracowywania tyflomap:

- mimo istnienia wielu algorytmów i modeli generalizacyjnych, nie istnieje holistyczne rozwiązanie, które byłoby w stanie jednocześnie przetworzyć całą mapę;
- istniejące opracowania automatycznego generowania tyflomap bazują na nieprzetworzonych danych przestrzennych, co prowadzi do powstawania map nieprzystosowanych do czytania przez ONS;
- brakuje rozwiązań automatycznego generowania tyflomap tematycznych, które mogłyby być wykorzystywane w edukacji. Istniejące rozwiązania skupiają się na tyflomapach do nawigacji i orientacji w terenie;
- brakuje współpracy między naukowcami a organami odpowiedzialnymi za opracowywanie map w poszczególnych krajach. Wiele rozwiązań, które sprawdziły się w danym kraju, nie zostało wytransferowanych poza jego granice.

Badania przedstawione w publikacji 4 przyczyniły się do realizacji celu głównego 2) oraz celu szczegółowego d).

Oba przeprowadzone przeglądy literatury (publikacje 3 i 4) umożliwiły wysunięcie wspólnego wniosku: dobre praktyki i sprawdzone rozwiązania z klasycznej kartografii powinno się przenosić na grunt tyflokartografii. Przykład takiego podejścia przedstawiłem wykorzystując klasyczne metody oceny wartości informacyjnej do oceny tyflomap (publikacja 1). Dotyczy to zarówno wytycznych generalizacyjnych, jak i innych rozwiązań z zakresu automatycznego generowania map. Jest to rozwiązanie bardziej zasadne, niż tworzenie nowych rozwiązań od podstaw. Wymaga jednak przyjęcia jednoznacznych reguł generalizacyjnych dostosowanych do zdolności percepcyjnych ONS. Należy również przyjąć standardy aktualizacji tyflomap, a wszystko to przy poszanowaniu zasad projektowania uniwersalnego.

Wyniki badań przedstawione w publikacjach 3 i 4 zostały wykorzystane do zaproponowania metodyki opracowywania tyflomap opisanej w publikacji 5. W metodyce tej zaimplementowałem także wyniki badań nad zwiększaniem potencjału informacyjnego tyflomap, przedstawione w publikacjach 1 i 2.

4.5. Metodyka półautomatycznego opracowywania tyflomap tematycznych [publikacja 5]

Tradycyjny sposób opracowywania tyflomap jest czasochłonny i mocno subiektywny. Skutkuje to brakiem powtarzalności uzyskiwanych produktów kartograficznych. Dlatego też podjąłem się badań nad zaproponowaniem metodyki półautomatycznego opracowywania tyflomap, która bazuje na koncepcji warstw kotwiczących i stanowi syntezę wyników pozostałych publikacji z niniejszego cyklu. Ich rozwinięciem jest zaproponowanie kompleksowej metodyki opracowywania i reprodukcji tyflomap z jednoczesną automatyzacją wybranych etapów. Proponowana metodyka dotyczy opracowywania map tematycznych, produkowanych z wykorzystaniem techniki druku 3D.

Zaproponowaną metodykę zweryfikowałem opracowując przykładową tyflomapę tematyczną, prezentującą wydobycie surowców mineralnych w Polsce. Zaproponowałem również nowatorskie podejście do opracowywania map hybrydowych z wykorzystaniem techniki druku 3D, składających się zarówno z treści dotykowej (w formie przezroczystej planszy), jak i graficznej (umieszczonej pod treścią dotykową), przystosowanych do czytania przez ONS. Przede wszystkim jednak, zaproponowaną metodykę można parametryzować według własnych potrzeb, co zapewnia szybkość i powtarzalność opracowywania tyflomap oraz stanowi istotny krok w kierunku pełnej automatyzacji tego procesu w przyszłości.

Bazując na wynikach poprzednich badań dotyczących wartości informacyjnej (Wabiński, Mościcka, & Kuźma, 2020), autorskich rozwiązań projektowych zwiększających czytelność i wartość informacyjną tyflomap (Wabiński, Śmiechowska-

Petrovskij, et al., 2022), jak również przeglądach literatury z zakresu automatycznego opracowywania map (Wabiński & Mościcka, 2019) oraz wytycznych projektowania tyflomap (Wabiński, Mościcka, & Touya, 2022), w niniejszym badaniu postawiłem następujące pytania badawcze:

1. Jakie procedury i zasady umożliwiają automatyzację i powtarzalność procesu tworzenia tyflomap tematycznych?
2. Które etapy tego procesu można w pełni automatyzować?

Proponowana metodyka jest dostosowana do wykorzystywania otwartych danych przestrzennych. Bazuje na jasno określonych i jednoznacznych parametrach, które można modyfikować według potrzeb. W opisanym studium przypadku, metodyka została przetestowana z wykorzystaniem druku 3D, ale może być także dostosowana do innych technik reprodukcji.

Podstawą przedstawionej metodyki jest koncepcja global master plan, zaproponowana przez Ruas & Plazanet (1997), która określa ogólny schemat redakcji mapy, pozostający zasadniczo niezmienny, niezależnie od wykorzystanej techniki reprodukcji, czy też grupy docelowej, dla której przygotowywana jest mapa. Procedura ta obejmuje następujące etapy:

1. wybór warstw kotwiczących i ich hierarchizację,
2. zdefiniowanie operatorów generalizacyjnych,
3. opracowanie mapy podstawowej,
4. dobór treści tematycznej i jej generalizację,
5. symbolizację i etykietowanie.

Szczegółowe parametry wymienionych kroków powinny być dostosowywane w zależności od mapy, która ma być opracowana w przyszłych zadaniach redakcyjnych.

4.5.1. Procedura opracowania mapy

Wybór warstw kotwiczących i ich hierarchizacja

Pojęcie warstw kotwiczących zostało zaproponowane przez Couclelis i in. (1987) i później rozwinięte przez Touya i in. (2021). W proponowanej metodyce warstwy kotwiczące są wykorzystane do przygotowania mapy podkładowej i pozostają wspólne dla każdej mapy w danym atlasie tematycznym lub serii map. Raz opracowane, pozostają niezmienne, niezależnie od dodawanej do nich treści tematycznej. Zatem wszystkie warstwy tematyczne muszą się dopasować do warstw kotwiczących i to one podlegają generalizacji przy opracowywaniu kolejnych map tematycznych - treść mapy podkładowej generalizowana jest tylko raz. Takie podejście ułatwia czytanie mapy, ponieważ czytelnik z dysfunkcją wzroku po zapoznaniu się z mapą podkładową, może w kolejnych krokach skupiać się jedynie na treści tematycznej pozostałych map w atlasie. Jako warstwy kotwiczące wybiera się najczęściej obiekty hydrograficzne, granice państw, główne miasta i pasma górskie.

Należy także ustalić hierarchię warstw kotwiczących na cele generalizacji, czyli nakreślić zasady dopasowywania się do siebie poszczególnych warstw z mapy podkładowej. Te niżej w hierarchii muszą zostać rozmieszczone w taki sposób, aby dopasować się do tych, które są w hierarchii wyżej.

Zdefiniowanie operatorów generalizacyjnych

W celu automatyzacji procesu tworzenia tyflomap, wykorzystałem pojęcie ograniczeń generalizacyjnych (generalization constraints). Dzielą się one na kilka kategorii: dotyczące czytelności (np. minimalny rozmiar znaku), kształtu (np. dosunięcie dwóch blisko leżących znaków liniowych), przestrzenne (np. maksymalne przesunięcie obiektów) oraz semantyczne (np. odsetek obiektów, które mają być zachowane w ostatecznym zbiorze danych).

Wszystkie ograniczenia generalizacyjne powinny być zastosowane w taki sposób, aby nie występowały konflikty kartograficzne, czyli takie konfiguracje znaków na mapie, które naruszają wytyczne dotyczące projektowania map lub zasady właściwej percepcji tychże znaków (Mackaness, 1994). W przypadku tyflomap tematycznych, możemy rozróżnić trzy podstawowe źródła konfliktów kartograficznych: ograniczenia percepcji dotykowej, nakładanie się treści tematycznej i podkładowej oraz wykorzystanie danych pochodzących z różnych źródeł. Podsumowanie wytycznych i dobrych praktyk dotyczących projektowania tyflomap zostało przedstawione w publikacji 3. Bazując na nich wybrałem konkretne wartości parametrów redakcyjnych i generalizacyjnych, które zostały wykorzystane w opisywanej metodyce, podczas opracowywania tyflomapy stanowiącej studium przypadku (Tabela 4).

Tabela 4 Parametry redakcyjne i generalizacyjne wykorzystane w studium przypadku

Parametr	Wartość	Źródło	Uwagi
Minimalna długość znaku liniowego	13 mm	(Edman, 1992)	wszystkie krótsze elementy zostały usunięte z mapy

Minimalna powierzchnia znaku powierzchniowego	3.2 mm^2	(Heath, 1958)	wszystkie mniejsze elementy zostały usunięte z mapy
Wysokość znaków dotykowych	0.3-1.5 mm	(ISO, 2019)	ustalono wysokość znaków powierzchniowych na 0,5 mm; liniowych na 1,0 mm; punktowych na 1,5 mm
Optymalny rozmiar znaku punktowego	4-6 mm	(The N.S.W. Tactual and Bold Print Mapping Committee, 2006)	ustalono rozmiar znaków punktowych na 5 mm
Optymalna szerokość znaku liniowego	0,5-0,8 mm	(Wiedel & Groves, 1969)	ustalono szerokość znaków liniowych na 0,8 mm
Minimalny odstęp między znakami w poziomie	1 mm	(Wabiński, Śmiechowska-Petrovskij, et al., 2022)	ustalono wartość 2 mm, co było możliwe dzięki zastosowaniu różnicowania wysokości znaków
Minimalny rozmiar etykiet czarnodrukowych	14-18 pt	(ISO, 2016; Polak & Olczyk, 2010)	nie powinno się stosować czcionek szeryfowych i z dekoracjami (np. kursywa)
Optymalny rozmiar etykiet brajlowskich	24 pt	(Więckowska et al., 2012)	rozmiar ustalony na podstawie standardu czcionki brajlowskiej Marburg Medium

Opracowanie mapy podkładowej

Przy opracowywaniu treści podkładowej dla mapy tematycznej, wykorzystałem otwarte dane przestrzenne z różnych źródeł. Pozyskane w ten sposób dane nie są przystosowane do percepcji przez ONS. Dopiero przeprowadzenie odpowiedniej generalizacji przystosowało je do czytania dotykiem i/lub uszkodzonym wzrokiem. Dane zostały poddane selekcji atrybutowej i lokalizacyjnej, wygładzeniu, oraz wyrównaniu, aby utrzymać relacje topologiczne występujące w rzeczywistości między mapowanymi obiektami. Proces ten został w pełni zautomatyzowany i przeprowadzony w module ModelBuilder oprogramowania ArcGIS. Na treść mapy podkładowej składają się: główne rzeki, największe miasta, woda morska oraz granice Polski i krajów sąsiednich.

Dobór treści tematycznej i jej generalizacja

Na treść tematyczną opracowanej mapy składały się tylko główne miejsca wydobycia konkretnych surowców mineralnych, przedstawione w formie znaków punktowych. Podobnie jak w przypadku danych tworzących mapę podstawową, tak i tutaj niezbędne było dostosowanie pierwotnych danych do umieszczenia na tyflomapie. W pierwszym kroku, wykorzystując przygotowany przeze mnie algorytm generalizacyjny, przeprowadziłem filtrację treści tematycznej ze względu na ważność poszczególnych miejsc wydobycia surowców mineralnych. Ustaliłem, że rzadziej występujące surowce mineralne, będą miały większy priorytet – algorytm stara się zachować obiekty tego typu. W następnym kroku, algorytm zlicza liczbę konfliktów graficznych, które dotyczą każdego znaku tematycznego. Te znaki, które nachodzą na największą liczbę innych, algorytm będzie się starał zachować. W tym kroku algorytm próbuje wyeliminować znaki tego samego typu występujące blisko siebie. Ostatecznie, algorytm zlicza liczbę znaków wokół każdego z nich, wewnątrz ustalonego bufora, i stara się zachować te bardziej odizolowane. Algorytm przyjmuje szereg parametrów wsadowych: skalę referencyjną opracowywanej mapy, rozmiary znaków oraz minimalne odstępy poziome między nimi, co umożliwia jego parametryzację.

Ponieważ wspomniany algorytm uwzględnia konflikty tylko między obiektami na warstwie tematycznej, niezbędna była niwelacja konfliktów kartograficznych zachodzących między elementami treści podkładowej i tematycznej. Do tego celu wykorzystałem platformę CartAGen (Touya, Lokhat, & Duchêne, 2019), a konkretnie algorytm random iterative displacement do odsunięcia elementów treści tematycznej, które wchodziły w konflikt geometryczny z elementami treści podkładowej, po połączeniu wszystkich warstw tyflomapy.

Symbolizacja i etykietowanie

Ze względu na ograniczenia percepcji ONS, liczba rodzajów znaków umieszczonych na pojedynczej tyflomapie powinna być ograniczona (Červenka et al., 2013; Rowell & Ungar, 2003). W omawianym przypadku, przygotowując mapę hybrydową, musiałem opracować dwa zestawy znaków: dotykowe oraz graficzne. Wybierając znaki na mojej mapie, bazowałem na istniejącej mapie przedstawiającej surowce mineralne Polski, pochodzącej z tyfloatlasu geograficznego Polski (GUGiK & PZN, 2004) oraz na moich doświadczeniach z poprzednich badań, w tym ze zidentyfikowanych zestawów znaków dotykowych opisanych w ramach publikacji 3.

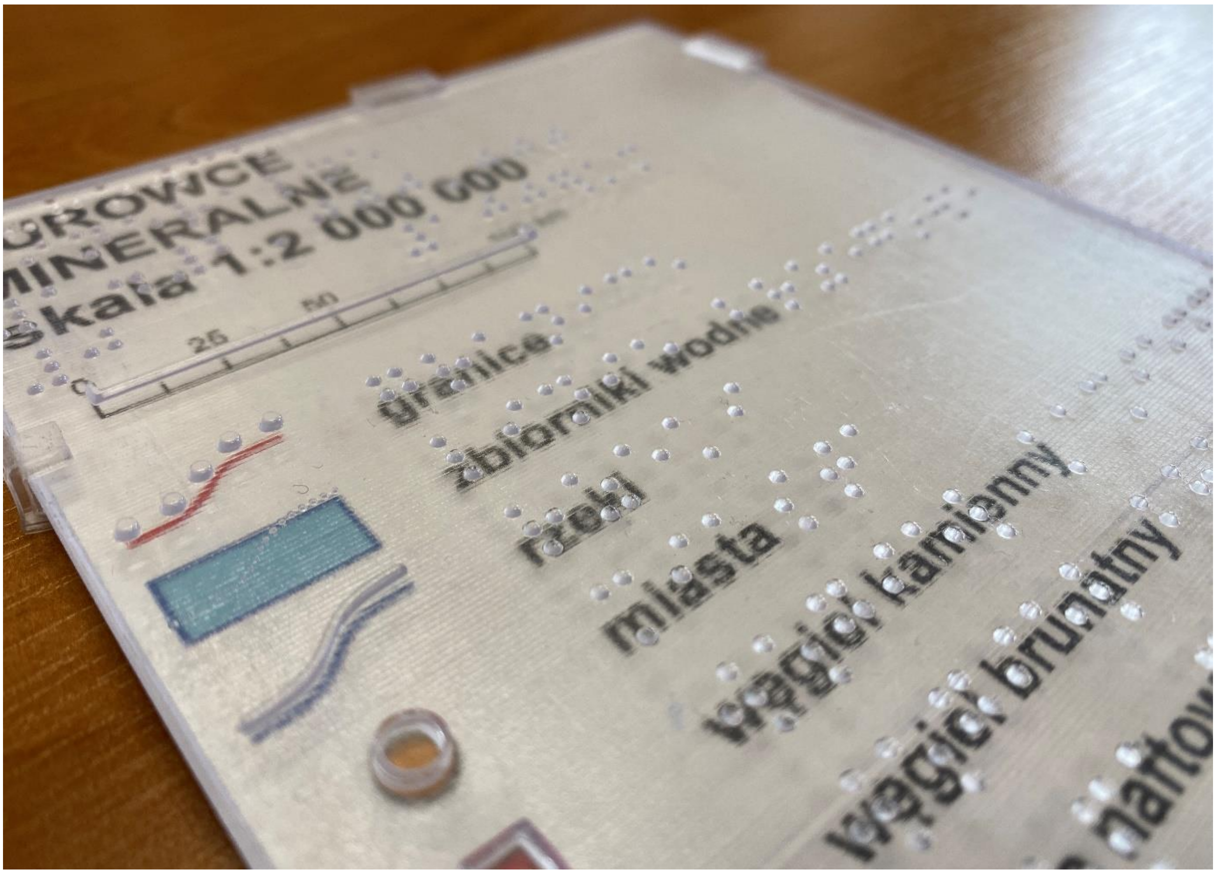
Przygotowałem również dwa zestawy etykiet: czarnodrukowe etykiety dla osób słabowidzących i brajlowskie etykiety wypukłe dla osób niewidomych. Etykietowanie zostało przeprowadzone automatycznie z wykorzystaniem Maplex Label Engine.

4.5.2. Przygotowanie arkusza mapy

Opisana wyżej procedura umożliwia automatyczne wygenerowanie płaskiej mapy wektorowej. Nie uwzględnia jednak przejścia z płaskiego rysunku na trójwymiarowy model, który będzie można wydrukować w 3D. Ten etap zrealizowałem manualnie, zgodnie ze zweryfikowaną wcześniej procedurą (Wabiński & Mościcka, 2017).

Mimo, że zaproponowana w publikacji 5 metodyka umożliwiła uzyskanie zadowalających wyników, zdecydowałem się na przeprowadzenie ręcznej edycji, która poprawiła czytelność mapy. Modyfikacje polegały między innymi na usunięciu niektórych elementów, które zwykle nie są umieszczane na podobnych opracowaniach, a które zostały zachowane przez algorytmy generalizacyjne. Niektóre etykiety nie zostały poprawnie rozmieszczone, dlatego poprzesuwałem je ręcznie. Zaaplikowałem także wysoko kontrastujące kolory do oznaczenia krajów sąsiadujących z Polską, aby poprawić czytelność warstwy graficznej.

Treść dotykowa arkusza mapy i jej legendy została wydrukowana w technologii SLA druku 3D, z wykorzystaniem przezroczystej żywicy. Graficzną część mapy wdrukowałem na kolorowym ploterze, a następnie obie mapy złączyłem za pomocą specjalnie zaprojektowanych zacisków, tworząc ostatecznie mapę hybrydową o wymiarach 36 na 34 cm. Procedurę powtórzyłem opracowując legendę mapy (Rys. 4).



Rys. 3. Legenda mapy hybrydowej opracowanej zgodnie z zaproponowaną metodyką.

4.5.3. Ocena opracowanej mapy

Na potrzeby oceny potencjału informacyjnego mapy, zliczyłem liczbę znaków poszczególnych rodzajów na trzech mapach przedstawiających to samo zjawisko: mapie pochodzącej z klasycznego atlasu szkolnego (Cacopulos et al., 2019), mapy z tyfloatlasu, na której bazowałem (GUGiK & PZN, 2004) oraz mapie opracowanej w ramach niniejszych badań. Jak się okazało, mimo dostosowania mojej mapy do wytycznych dotyczących projektowania tyflomap, a więc przeprowadzenia silnej generalizacji w sposób automatyczny, udało się umieścić na niej zdecydowanie więcej treści (115 znaków, w tym 79 tematycznych), niż znajduje się na istniejącej tyflomapie z 2004 roku (64 znaki, w tym 31 tematyczne).

Sam fakt umieszczenia więcej treści nie oznacza jednak, że mapa jest użyteczna. Opracowany w tym badaniu arkusz mapy przetestowałem z udziałem uczniów pierwszej (9 osób) i drugiej (4 osoby) klasy Liceum Ogólnokształcącego dla Dzieci Niewidomych i Słabowidzących w Laskach. 8 uczniów posługujących się widzeniem resztkowym oceniało zarówno wariant dotykowy, jak i graficzny opracowanej tyflomapy.

Uczniowie zostali poproszeni o wykonanie zadań symulujących pracę na lekcji geografii, z wykorzystaniem opracowanej przeze mnie mapy. Zadania polegały na policzeniu miejsc wydobycia poszczególnych rodzajów surowców mineralnych, wskazaniu rodzaju surowca wydobywanego w danej okolicy, czy opisaniu kształtu oraz koloru danego znaku na mapie. W przypadku wariantu dotykowego tyflomapy, uczniowie odpowiadali na pytania ze skutecznością na poziomie 75-78%.

Uczestnicy badania pozytywnie ocenili komfort dotykowy tyflomapy, jednak zwrócili uwagę na mankamenty związane z czytelnością wariantu graficznego. 5 z 8 uczniów oceniających wariant graficzny miało problemy z odczytaniem graficznej treści mapy. Ci sami uczniowie zaproponowali kilka możliwych do wdrożenia poprawek. Znaki punktowe powinny być większe, a etykiety brajlowskie nie powinny nakładać się na te czarnodrukowe. Pozostałych 3 uczniów oceniających treść graficzną potrafiło rozwiązać przedstawione zadania i rozróżnić kolory użyte na mapie.

Mankamenty treści graficznej mapy są możliwe do zniwelowania, jednak wymagają dopracowania wykorzystanej przeze mnie technologii druku 3D. Wykorzystana do wydruku dotykowej nakładki żywica nie była w pełni przezroczysta, co było spowodowane niewłaściwym czyszczeniem arkusza mapy.

Podsumowując, poprzez zaprezentowanie metodyki, udało się wypełnić luki zidentyfikowane w ramach analizy dotychczasowego stanu wiedzy (publikacje 3 i 4). Opisane wyżej etapy stanowią bezpośrednią odpowiedź na pierwsze pytanie badawcze. Badanie potwierdziło, że zaproponowana metodyka umożliwia półautomatyczne opracowywanie tyflomap tematycznych. Procesy selekcji atrybutowej i lokalizacyjnej, wygładzania, wyrównywania oraz rozmieszczania elementów na tyflomapie udało się w pełni zautomatyzować, co stanowi odpowiedź na drugie pytanie badawcze. Pozostałe elementy metodyki, takie jak wybór warstw kotwiczących i ich hierarchizacja oraz symbolizacja i etykietowanie, pomimo braku pełnego zautomatyzowania na tym etapie, zostały szczegółowo opisane za pomocą jednoznacznych reguł i wytycznych, co umożliwia zniwelowanie subiektywizmu osoby opracowującej podobne tyflomapy tematyczne w przeszłości.

Sama metodyka może być w prosty sposób modyfikowana i parametryzowana do opracowywania w przyszłości map prezentujących inne zagadnienia, dla innych grup odbiorców oraz przy użyciu innych technik reprodukcji. Jej szersze zastosowanie może prowadzić do pełnej standaryzacji w zakresie opracowywania tyflomap, co jest normą w przypadku klasycznych map topograficznych.

Zaproponowana metodyka umożliwia uzyskanie powtarzalnych wyników, jednocześnie redukując czas i koszty produkcji. Jej użyteczność została zweryfikowana w trakcie testów z uczniami niewidomymi i słabowidzącymi, co potwierdza wysoką czytelność produktu finalnego.

Badania przedstawione w publikacji 5 umożliwiły osiągnięcie celu szczegółowego d) i przyczyniły się do realizacji celu głównego 2.

5. WNIOSKI I PODSUMOWANIE

Spójny tematycznie cykl pięciu publikacji, pt. „Metodyka zwiększania potencjału informacyjnego oraz półautomatycznego opracowywania tyflomap", który stanowi niniejszą rozprawę doktorską, miał na celu przedstawienie oryginalnego podejścia do opracowywania tyflomap z wykorzystaniem druku 3D. Zaproponowana przeze mnie metodyka umożliwia optymalizację ilości informacji przekazywanych za pomocą systemu znaków kartograficznych, a następnie opracowanie czytelnej mapy w sposób półautomatyczny.

Teza niniejszej rozprawy doktorskiej brzmi: **„wykorzystanie pełnego potencjału zmiennych haptycznych oraz parametryzacja procesu opracowywania tyflomap zapewnia powtarzalne generowanie tyflomap o wyższej wartości informacyjnej"**. Wynikała ona z faktu, że tyflomapy za pomocą swojej silnie uogólnionej treści przekazują niewiele informacji, zaś proces ich opracowywania był nieunormowany, subiektywny i czasochłonny. Przeprowadzone w ramach rozprawy doktorskiej badania dotyczyły sposobu zwiększania ilości informacji umieszczanych na tyflomapach poprzez wykorzystanie pełnego zakresu zmiennych haptycznych w projektowaniu znaków tyflograficznych i ujednolicenia zasad opracowywania tyflomap, a także parametryzacji sposobu projektowania znaków tyflokartograficznych i procesu redakcji mapy, jak również automatyzacji najtrudniejszych etapów przygotowywania map dla ONS.

Do badania zasobu informacyjnego tyflomap zaproponowałem wykorzystanie klasycznych metod oceny ilości informacji na mapach, bazujących na wskaźnikach liczbowych (publikacja 1). Udowodniłem, że strukturalną miarę informacji oraz współczynnik wydajności informacyjnej można z powodzeniem zastosować także w tyflokartografii, jeżeli zamiast zmiennych graficznych do oceny liczby informacji zawartych w poszczególnych znakach wykorzysta się zmienne haptyczne, potwierdzając tym samym pierwszą hipotezę badawczą (H1). Wyniki tych badań umożliwiły mi obliczanie ilości informacji umieszczanych na tyflomapach. Możliwość tę wykorzystałem do oceny, czy, i w jaki sposób, zmienia się ilość informacji na tyflomapie, gdy do konstrukcji systemu znaków zastosuję pełen zasób zmiennych haptycznych (publikacja 2). Udowodniłem, że jeśli do projektu znaków tyflokartograficznych wprowadzę rzadko dotychczas stosowane różnicowanie ich wysokości, to mapa będzie na tyle czytelna dla użytkowników, że możliwe będzie zmniejszenie minimalnych odstępów między nimi z rekomendowanych 3-5 mm do nawet 1 mm i umieszczenie dzięki temu więcej treści na pojedynczym arkuszu mapy, a w konsekwencji opracowywanie map o większej wartości informacyjnej. Tym samym potwierdziłem drugą hipotezę badawczą (H2).

Wyniki badań przedstawione w publikacjach 1 i 2 umożliwiły osiągnięcie pierwszego celu badawczego.

W badaniach nad ujednoliconymi zasadami opracowywania tyflomap wykorzystałem dotychczasowe doświadczenia w zakresie projektowania tyflomap (publikacja 3) oraz algorytmów i/lub modeli generalizacji danych przestrzennych (publikacja 4) do wskazania rozwiązań, które mogą być wykorzystane w ujednoliconej procedurze opracowywania tyflomap w sposób przynajmniej częściowo zautomatyzowany.

Znajomość dobrych praktyk dotyczących projektowania i rozmieszczenia elementów na tyflomapach, algorytmów i modeli generalizacyjnych oraz istniejących rozwiązań z zakresu automatycznego opracowywania tyflomap umożliwiła zaproponowanie metodyki półautomatycznego opracowywania czytelnych i kartometrycznych tyflomap tematycznych (publikacja 5). Zaproponowałem etapy opracowania map tematycznych, które są niezależne od techniki druku oraz przedstawiłem zasady ich realizacji. Opisałem procedurę doboru oraz generalizacji treści podkładowej i tematycznej tyflomap, jak również parametry liczbowe związane z redakcją mapy, które powinny być dobierane pod kątem konkretnej techniki druku. W metodyce tej zaimplementowałem także autorski sposób zwiększania ilości informacji na mapie poprzez wykorzystanie wszystkich zmiennych haptycznych.

Poprawność proponowanych rozwiązań sprawdziłem opracowując prototypową tyflomapę tematyczną zgodnie z zaproponowaną metodyką. Udowodniłem, że precyzyjne zdefiniowanie parametrów dotyczących cech geometrycznych znaków tyflokartograficznych i redakcji treści mapy - czyli tych, które mają wpływ na czytelność, a także jednoznaczne opisanie sposobu postępowania w trakcie opracowania mapy, umożliwia automatyzację najbardziej skomplikowanych etapów tej procedury. W konsekwencji, gwarantuje to powtarzalność procesu opracowywania tyflomap. Tym samym potwierdziłem trzecią hipotezę badawczą [H3].

Wyniki badań przedstawione w publikacjach 3, 4 i 5 umożliwiły osiągnięcie drugiego celu badawczego.

Przeprowadzone badania udowodniły zarówno możliwość powtarzalnego generowania tyflomap, jak i uzyskania wyższej wartości informacyjnej tyflomap opracowywanych z wykorzystaniem proponowanych przeze mnie rozwiązań. Potwierdzają one zatem prawdziwość postawionej na wstępie tezy, że „**wykorzystanie pełnego potencjału zmiennych haptycznych oraz parametryzacja procesu opracowywania tyflomap zapewnia powtarzalne generowanie tyflomap o wyższej wartości informacyjnej**”. Należy przy tym podkreślić, że wszystkie proponowane autorskie rozwiązania były na bieżąco weryfikowane przez ONS pod kątem czytelności i komfortu pracy, dzięki czemu moje rozwiązania mogą być już dzisiaj z powodzeniem wykorzystywane w praktyce.

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ZAŁĄCZNIKI

Artykuły stanowiące cykl publikacji wraz z oświadczeniami współautorów o procentowym udziale w poszczególnej publikacji:

1. **Wabiński, J.** (80%), Mościcka A. (20%) (2019) Automatic (tactile) map generation—a systematic literature review. *ISPRS International Journal of Geo-Information*, *8*(7). https://doi.org/10.3390/ijgi8070293
2. **Wabiński, J.** (70%), Mościcka, A. (20%), & Kuźma, M. (10%) (2020). The Information Value of Tactile Maps: A Comparison of Maps Printed with the Use of Different Techniques. *The Cartographic Journal*, *58*(2), 123–134. https://doi.org/10.1080/00087041.2020.1721765
3. **Wabiński, J.** (60%), Śmiechowska-Petrovskij, E. (30%), & Mościcka, A. (10%) (2022). Applying height differentiation of tactile signs to reduce the minimum horizontal distances between them on tactile maps. *PLOS ONE*, *17*(2). https://doi.org/https://doi.org/10.1371/journal.pone.0264564
4. **Wabiński, J.** (70%), Mościcka, A. (20%), & Touya, G. (10%) (2022). Tactile maps design guidelines standardization: literature and best practices review. *The Cartographic Journal*. https://doi.org/10.1080/00087041.2022.2097760
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REFEREED PAPER

The Information Value of Tactile Maps: A Comparison of Maps Printed with the Use of Different Techniques

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ABSTRACT
Visually impaired people use tactile maps that can be read by the sense of touch or, to a limited extent, with their eyes. This article concerns the methods of assessing tactile maps in terms of their information value. In the research, methods used to assess traditional maps have been adopted to assess tactile maps. Tactile elements of two maps – one developed with the use of traditional methods and the second developed with the use of 3D printing – have been compared. Structural measures of information as well as the information efficiency coefficient of each map have been determined to assess whether new cartographic symbols proposed on a multi-level 3D printed map can increase its information value.

KEYWORDS
Information value; structural measure of information; tactile maps; map analysis; 3D printing; blind and visually impaired

Introduction

The process of map assessment is considered part of cartography theory (Arnberger, 1966). When evaluating maps, one should take into account both the utilitarian purpose and aesthetic values. The assessment process can be divided into three main stages: determining the subject and purpose of the assessment, selection of assessment criteria and techniques, and, finally, the presentation and verification of evaluation results (Kałamucki, 1998). The aforementioned assessment techniques can be quantitative or qualitative. However, it is the map's intended use that determines how it should be designed: the selection of content, the classification of this content, the choice of presentation methods, generalization standards and the general information resource (Salistchev, 2002).

Over the years, cartographers have developed a number of criteria for assessing the cartographic form of communication. Boczarow (1966) distinguishes between the legibility of the map, statistical regularity of the visual perception of cartographic symbols, and the graphic and numerical load of the map. The author describes some of these parameters in detail. One of the examples is the graphic load of a map, which is defined as the area that is covered by all graphic elements on the map. The same approach was also proposed by Fiłatow (1988). However, Salistchev (2002) showed the weakness of this approach. He pointed out that changing the size of cartographic symbols would be visible in the change of the graphic load of a map but at the same time, this action would not provide any additional cartographic information. This is why he suggests using methods of mathematical information theory, if we wish to make an objective evaluation of spatial unification (or differentiation) of phenomena and their mutual compatibility (Shannon, 1948). One of the basic functions of this theory is entropy that can be used to define the heterogeneity of the cartographic image – as an indicator of spatial diversity of phenomena. The pioneering work on using this approach in the quantitative assessment of map information was done by Sukhov (1967), but it has been commonly used until the present day (Li and Huang, 2002; Harrie and Stigmar, 2010). Salistchev (2002) also proposes using a structural measure of information to assess a map. This approach is based on calculating the amount of information as the sum of quantities characterizing the informational significance of symbols that depict discrete objects, with respect to the number of information elements contained in each sign. Every difference in the position or characteristics of objects is measured in this approach.

However, all the methods described above apply to maps that are based on classic cartographic symbol features used on maps, such as shape, size, grain, orientation, value and hue (Bertin, 1967). To the best of our knowledge, there is no research in this field regarding tactile maps for blind and visually impaired people. These show graphic information using relief and tactile symbols and are normally used with corresponding legends (Gual *et al.*, 2015); they are read by the sense of touch or, to a limited extent, by eye (Ojala *et al.*, 2016). Tactile maps are based on haptic variables, such as height, size, grain, profile, shape, texture, orientation, temperature, and resistance. The juxtaposition of these two kinds of variables is presented on Figure 1.

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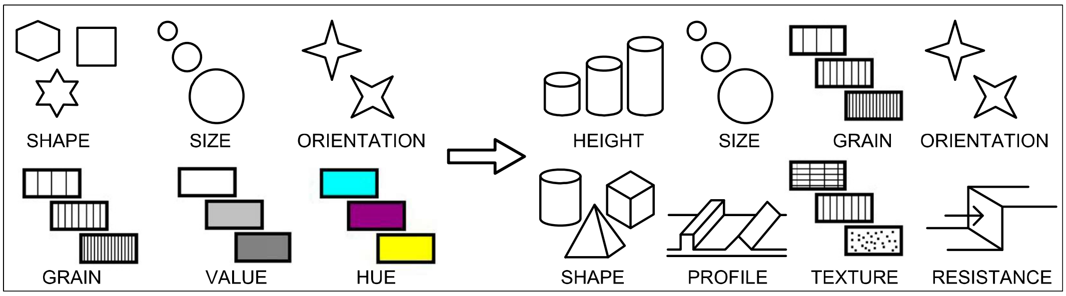


Figure 1. Graphic variables and the most important haptic variables.

All maps have to be legible. An average person, without any visual impairment, can distinguish two points or lines as separate under normal viewing conditions if they are 0.15 mm apart from each other (Yanoff and Duker, 2009). To distinguish two points as separate with the use of touch, they have to be at least 2.4 mm apart from each other (Klatzky and Lederman, 2003). Persons without vision impairment usually see the whole map sheet at once with their eyes. Blind and visually impaired people read the map in fragments and memorize them (Olczyk, 2014). The symbols commonly used in traditional cartography are usually too small or too complicated to be read correctly using the sense of touch or a damaged sense of sight, even after raising them to a spatial form. This makes tactile maps less detailed and requires them to be printed in larger formats (Edman, 1992).

Moreover, tactile map production is very expensive. Methods commonly used for their production: plastic thermoforming or relief screen printing are only cost-effective for large-volume production. This leads to a situation where blind and visually impaired people do not have access to as much spatial information as others. In the face of these restrictions, research is underway to improve the process of tactile map production. New production methods are also being tested. These include additive methods (also called 3D printing) (Voženílek *et al.*, 2009; Götzelmann and Pavkovic, 2014; Gual *et al.*, 2014; Taylor *et al.*, 2016; Wabiński and Mościcka, 2017). This technology is characterized by a fixed, low unit cost and it allows rapid prototyping. The cost of performing tests with different materials, symbol shapes and arrangement of map content is relatively low. This method also allows tactile-map designers to fully experiment with the appearance of a tactile map.

Taking the above into consideration, the aim of this paper is to compare the information value – understood as 'the level of satisfying the information needs of the user' (Potelarska-Walczyńska, 1979) – of a tactile map produced with use of traditional methods with one developed by 3D printing that enables the use of new cartographic symbols that can be designed freely, as 3D printing can print almost everything that is designed. Therefore it is important to analyse their impact on the information value of a tactile map. This leads us to the research question: how does the production method used affect the cartographic information value of the tactile map? This question is related to a subsequent question: do the new cartographic symbols used on 3D printed maps increase the information value of a map? And most importantly: can the methods for computing the information value of classic maps be applied to tactile maps?

Materials and methods

The study described in this paper aims to measure the information value of sample elements of tactile maps and, at the same time, compare this value on two maps presenting the same geographical phenomenon but prepared using different production methods. This approach is innovative not only because so far there have been no attempts to measure the cartographic information value on tactile maps described in literature, but also because one of the compared maps represents a novel approach to tactile map generation (Wabiński, 2017). Therefore, we examine whether methods for measuring cartographic information value on classic maps can be applied to tactile maps and how the method of production of a tactile map influences these measures.

Maps used in the research

The first map, for the purpose of this paper referred to as the 'original map from atlas', comes from the 'Atlas of the Nature for the Blind – Volume 1' issued in 2010 (Atlas do przyrody dla osób niewidomych i słabowidzących – TOM 1 Polska, 2010) that is commonly used in schools for the blind and visually impaired in Poland. It is the 'p3 – Poland – Geographical Regions' map prepared in a foldable A2 format in a scale of 1:2 000 000. It presents the main geographical regions of Poland along with the main rivers and lakes. The atlas is built of cartographic and textual content. The cartographic part consists of 34 map sheets in A2 or A3 format. Volume 1 contains 15 sheets and a legend in A4 format that focus on Poland, designed in scales 1:200 000, 1:400 000, 1:750 000 and 1:2 000 000. The textual part consists of: 'Explanation of abbreviations used on map' written in Braille and in classic black font The publication also includes an audio compact disc (CD) containing the 'Student's guide' and 'Methodological guidelines for the teacher'. Each text on the CD explains the content of a particular map and allows student to work independently or with the help of their parents or teacher. The map, as well as the entire atlas, was created with the use of transparent relief print imposed on a coloured base, suitable for both blind and visually impaired students. This solution allows obtaining a relief print but with a certain limitation – all the elements are raised to the same, fixed height (Atlas do przyrody dla osób niewidomych i słabowidzących – TOM 1 Polska, 2010).

The second map used in this research was developed as a part of an MSc thesis (Wabiński, 2017) using 3D printing technology, more specifically Fused Deposition Modelling that uses thermoplastic material to form a physical model layer by layer on the 3D printer's surface. A tactile map presenting the geographical regions of Poland (Wabiński, 2017), similar to that described previously, was developed with the help of tactile pedagogues working at the Society for the Care of the Blind in Laski (Towarzystwo Opieki nad Ociemniałymi w Laskach, 2019). The designed map is based on 'good practices' in the field of tactile map design (Edman, 1992; Braille Authority of North America and Canadian Braille Authority, 2011) and complies with the current curriculum. However, some modifications were introduced, resulting from the possibilities of 3D printing technology. The map sheet was created in A3 format, which is considered as an optimal format that takes into account the maximum reach of the reader's arms (Gual, Puyuelo and Lloveras, 2012). This defined, basing on the map extent, the scale of the map: 1:3 000 000.

Thanks to the use of 3D printing technology it was possible to eliminate the disadvantages of the original map from atlas and to develop a multi-level map. It means that an additional variable – height – was used, as an element differentiating objects on the map. On the 3D printed map individual geographic regions are extruded to different heights depending on the average altitude above the sea level in a given area. This is a novel solution, unheard of in the existing literature. Because of the modification described above, line symbols depicting rivers run through different geographical regions (at different heights), so another solution had to be found. In order to follow the course of the river from its source to the estuary, special ramps were designed that transfer river symbols between individual geographical regions, without disturbing their course. These ramps rise and fall at 45 degrees (Wabiński and Mościcka, 2017). The 3D printed map was tested by four pupils from the school run by Society for the Care of the Blind in Laski (Towarzystwo Opieki nad Ociemniałymi w Laskach, 2019). At the time of testing, two of the pupils were at the primary school level, while another two were at the level of secondary school. 2 of the students were blind and two with severe visual impairment. The pupils were asked to solve six tasks that simulated an exemplary geography class. The map was assessed by them as clear and understandable but they suggested some possible amendments (Wabiński, 2017). The comparison of characteristics of the two maps is presented in Table 1.

Both maps (Figures 2 and 3) were developed in accordance with good practices described in literature (Edman, 1992; Braille Authority of North America and Canadian Braille Authority, 2011; Lawrence and Lobben, 2011; Wang *et al.*, 2012) as well as tested and used by blind people. Both maps are readable for them so neither the degree of readability nor cartographic editing were the subject of our research. Although the scales of the maps are different, the degree of generalization of their content as well as the scope of tactile content are almost the same. So, these maps can be compared in terms of the amount of tactile information they provide, because only tactile elements designed for the blind people have been used in the research. The coloured elements used on the original map from atlas and designed for visually impaired people have not been taken into consideration. Because the map contents are almost the same, it was assumed that the ability of their readers (blind students) to read them is the same. The method of using these maps, which may be different in the case of a single map and an atlas map, does not influence the research results, because only the information value of particular tactile signs has been determined.

Map comparison principles

In order to measure the information values of tactile elements on both maps, we have calculated structural measure of information, in a way proposed by Salistchev (2002). It consists of calculating the amount of information as the sum of quantities characterizing the informational significance of cartographic symbols according to the number of information each symbol provides. Each difference of objects in terms of position and properties is considered as a unit of measurement. The Salistchev approach previously used for evaluation of traditional maps was adapted for tactile maps. The way of calculating structural measure of information was generally the same as in the original Salistchev method. The only difference in the proposed methodology is that instead of graphical variables distinguishing symbols three-dimensional haptic variables were used. The challenge here was to identify the

Table 1. Characteristics of maps compared in the research.

Parameter	Original map from atlas	3D printed map
Map sheet dimensions	595 × 420 mm	420 × 297 mm
Data frame dimensions	374 × 340 mm	246 × 232 mm
Scale	1:2 000 000	1:3 000 000
Joints	Folded sheet (2 equal parts), Distortion: approximately 1 mm	Rectangular segments with dovetail joints (6 parts), Distortion: negligible
Meridians and parallels	Insets on the edge of data frame every 1° of lat/lon (even values described)	Insets on the edge of data frame every 1° of lat/lon (odd values described)
Numerical/linear scale	Top left/top right corner	Top edge of the sheet/top right corner
North indication	Top right corner – convex triangle	Top right corner – convex triangle
Additional features	• coloured base • part of an atlas • multimedia guide for the student • wind rose	• height differentiation • ramps used to transfer linear signs • can be washed • durable

variables used for cartographic symbol differentiation correctly. For classic maps, the most commonly used graphic variables are those proposed by Bertin (1967). Unfortunately, they cannot be used in case of tactile maps as these require the use of a different set of variables – haptic variables. Haptic sciences are divided into two main components: one refers to skin sensations caused by touch and the other related to muscle mechanics. Previous research has led to the construction of a set of haptic variables that include those associated with the impression of touch and can be used to describe cartographic signs on tactile maps (Griffin, 2001; McCallum *et al.*, 2005). During this research, we focused on blind readers and have taken into account only the haptic variables useful for blind readers. The reason is that one of the maps used for comparison is suitable only for blind users (i.e. the 3D printed map).

Salistchev (2002) proposes to first assign to every cartographic symbol used on the map the quantity of information it presents. These values are then used to weigh the individual symbols in order to compute the amount of information. This approach can be visualized by a simple example. A cartographic point symbol representing a residential area provides information on the location of this area in the real world, which is a default property of objects on maps, but it can also provide additional information, such as population or administrative significance. In order to differentiate this kind of point symbol, a number of graphic variables has to be used. The appearance of a cartographic symbol representing a city on a regular topographic map can be differentiated by changing its size, hue or value. So in the given example more populated cities can be indicated by bigger symbols, while capital cities can be depicted by using different hues than any other cities on a map (Salistchev, 2002).

In order to measure the structured information value correctly, it is necessary to compute the number of cartographic symbols of each type on the map. While the job is fairly easy in case of point symbols – they have to be counted one by one, for line and area symbols a different approach has to be used. It is necessary to apply geometric measures, i.e. the measurement of the length of individual symbols and then to multiply these measures by the quantity of information represented by the symbol of the corresponding object. As far as area symbols are concerned, their territorial differentiation and fragmentation is reflected in the lengths of their boundary lines (Salistchev, 2002).

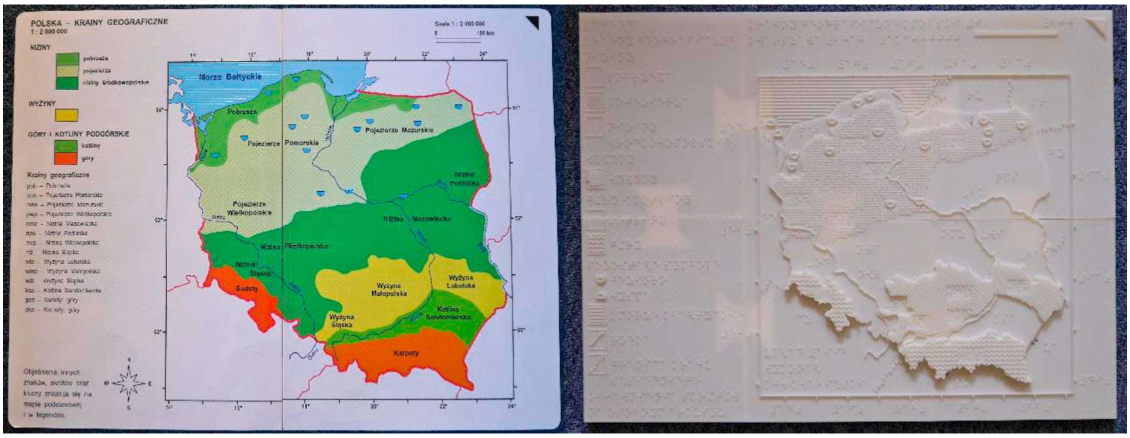


Figure 2. The maps used in the research: overview. On the left side – original map from atlas, source: (Atlas do przyrody dla osób niewidomych i słabowidzących – TOM 1 Polska, 2010). On the right side – 3D printed map, source: authors.

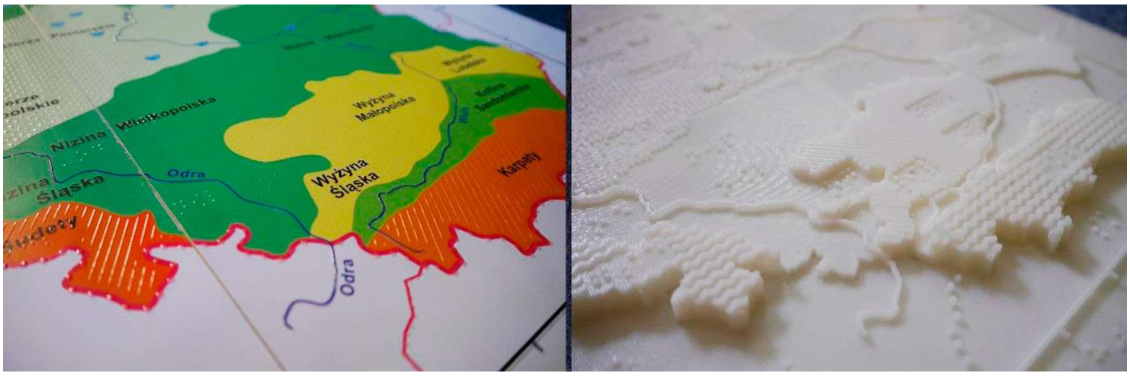


Figure 3. The maps used in the research: zoom-in. On the left side – original map from atlas source: (Atlas do przyrody dla osób niewidomych i słabowidzących – TOM 1 Polska, 2010). On the right side – 3D printed map, source: authors.

For these measurements we used real-scale flat vector drawings of both maps (Figure 4). In order to facilitate the process of determining the information value and to provide additional material for analysis, these drawings were divided into segments. As both maps are characterized by different scales (1:2 000 000 for the original map from the atlas, 1:3 000 000 for the 3D printed map), it was necessary to divide them into the same number of segments but different in size. We determined the optimal number of segments empirically and it amounted to 36 (if a point symbol fell on the border of the segments, we then determined the centre of the symbol's bounding box to indicate the segment that it should belong to). All the measurements were carried out using Rhinoceros 3D software. In order to analyse the spatial distribution of information values on both maps, these values were measured independently for each segment.

We calculated the structural measure of information with the use of the proposed methodology, for particular segments of each map as well as for the whole maps. On the basis of the above assumptions, structural measure of information (*SMI*) was calculated basing on the formula:

$$SMI = \sum_{i=1}^{n} SMI_i \tag{1}$$

where n is the number of segments, SMI_i is the structural measure of information of particular map segment.

Structural measure of information of particular map segment (SMI_i) has been calculated basing on the formula:

$$SMI_i = \sum_{i=1}^{k} a_i * p_i + \sum_{i=1}^{l} b_i * p_i + \sum_{i=1}^{m} c_i * p_i \tag{2}$$

where k, l, m is the number of particular types of point, line and area cartographic symbols in map segment, a_i is the number of point symbols of particular type in map segment, b_i is the length of linear symbols of particular type in map segment, c_i is the length of boundary lines of particular type of area symbol in map segment, p_i is the number of information assigned to a particular symbol type (sign's weight).

While calculating the lengths of line symbols and area borders it was important to reduce measurements to the same scale. In this case, the values measured on flat vector drawings were expressed in the map scale. Thus, it was necessary to apply a scale factor. We multiplied values measured on the 3D printed map by a scale factor of 1.5, which shows the ratio of the scales of both maps used in the research.

It is not possible to compare the measurements of points, lines and area symbols directly, as they are measured in a different way. Therefore in order to compare the results obtained from measurements carried out on both maps, it was necessary to normalize the raw results. The normalization process also enables free choice of the way of measuring particular values on maps. It does not matter whether values measured will be expressed in the map scale or in real (terrain) values as long as they will be normalized later.

The final data should not have negative values and ought to range from 0 to 1. This is why the authors decided to use the simple min–max normalization method (Larose, 2005) based on the following formula:

$$V' = \frac{V - V_{\min}}{V_{\max} - V_{\min}} \tag{3}$$

where V' is the normalized value, V is the original measured value (number of a specific type of point symbol or length of a particular line or area symbol in a particular map segment), $V_{\min}$ or $V_{\max}$ is the minimum or maximum value measured on both maps.

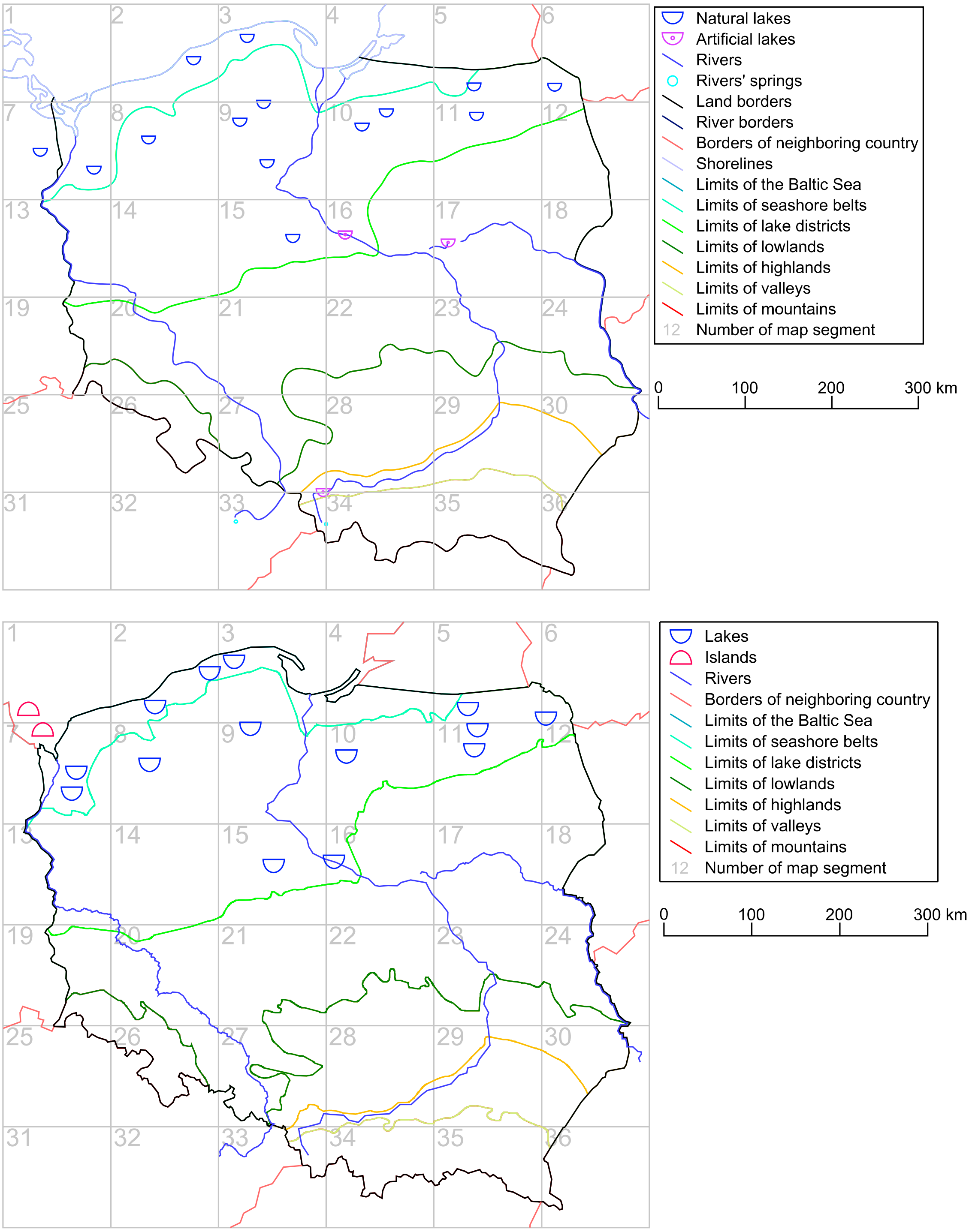


Figure 4. Flat vector drawings used for calculations. On the top – original map from atlas, at the bottom – 3D printed map, source: authors.

Additionally, we decided to distinguish two categories of information presented on the maps: thematic (geographical regions) and background. A structural measure of information was calculated both for the entire map and separately for the background and thematic data. Moreover, dividing maps into segments enables to perform an analysis of the distribution of the values of the structural measure of information of both maps to show the information density and its spatial arrangement. Therefore, we have created maps of distribution of the values of the structural measure of information of each map, as well as a map of value differences on both maps.

Knowing the number of individual pieces of information that the cartographic symbol provides, it was possible to compute the information performance of a cartographic symbol, proposed by Grygorenko (1973) and called the information efficiency coefficient of a map (W). Instead of graphic variables, Grygorenko uses cartographic means of expression, that is all graphic elements used to create symbols, which not only differentiate symbols from each other, but also affect the readability of the map. For the purpose of tactile map assessment, the Grygorenko formula of information efficiency coefficient calculation was adopted in the following form:

$$W = \frac{i}{z} \tag{4}$$

where W is the information efficiency coefficient of a map, i is the number of pieces of information given by all cartographic symbols present on a map, z is the number of all cartographic means of expression used to create cartographic symbols present on a map. This coefficient can be also computed for each cartographic symbol used on a map. According to Grygorenko, its optimal value should be equal to one – then one graphic symbol is used to transmit one piece of information.

Since Braille writing takes up much more space than the traditional one (because of larger characters), one should not only limit the descriptions of the objects constituting the basic content of the map but also apply the appropriate code system. A common solution in Polish tactile cartography is that three-character abbreviations are used, where the first character is the category code and two consecutive ones identify the presented object uniquely (Więckowska *et al.*, 2015). When describing a geographical object, e.g. a river, the first letter of the code means the category and the rest stands for the particular name of the object. It was not possible to define how to efficiently measure these inscriptions. This is why at this stage of research we did not take map inscriptions into account. We have computed only the total number of each type of inscriptions that appears on both maps.

Results

The analysed maps were created with the use of different production techniques. A list of all symbols along with the number of information and haptic variables used is presented in Tables 2 and 3. It is worth mentioning that the haptic variable of shape, in case of tactile maps, represents a three-dimensional shape and therefore there is no need to identify height as a separate variable. The only exception here is when symbols within one category are differentiated by height variable. The same applies to textures. For example, in case of a symbol representing the Baltic Sea, the only variable used here is texture, which determines its three-dimensional shape. At the same time, this symbol provides only one piece of information – position. The haptic variable of texture is also used to represent geographical regions, but in case of 3D printed map, individual geographical regions are also differentiated by height. This results in two haptic variables used (texture and height) and provides the user with three types of information: the position of a geographical region, its type and mean height.

In order to enable the comparison of the two examined maps, the same symbol categories had to be used. This is why, even though in some categories there were zero symbols on a particular map, these categories are still present in the table. As during the research we used the final products (maps), rather than developed them from the scratch, it was not possible to have exactly the same categories of cartographic symbols. This results for example in the presence of point symbols representing river springs on the original map from the atlas that do not exist on the 3D printed map.

In order to use the obtained results for comparison, we normalized all the symbol categories, using the previously described min–max method (formula (3)). We then summed these individual results to provide information on the structural measure of information in each segment (SMI_i – formula (2)) and on each map (SMI – formula (1)). Tactile maps, as well as their classic counterparts, contain thematic and background content. In case of the map of geographical regions of Poland particular regions (e.g. lowlands or mountains) form the thematic content. We checked the portion of total information value that was included in the thematic content of each examined map using the methods described above. The results are presented in Table 4.

It is clearly visible that the 3D printed map is characterized by a higher total cartographic information value, which provides the answer to the first and second research questions. It confirms that 3D printing and multi-level symbols improve the value of information of tactile map. Besides, using the methods described, we demonstrated that over 53% of the information value of the 3D printed map is represented by area symbols of geographical regions (thematic content). The original map from atlas, on the other hand, contains approximately 13% less information than its 3D printed counterpart, while at the same time less than 35% of the information value is represented by thematic content.

The division of maps into segments allows to perform an analysis of the distribution of the structural measure of information values (namely information density) of both maps (Figure 5). This might help in the future design of tactile maps, as it can be easily seen where the density of information is the highest and where is the lowest. Such information may prove invaluable as tactile maps require a certain level of generalization to keep the maps legible and optimizing the data distribution process is of high importance.

Table 2. Map symbols and number of information assigned to them – original map.

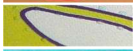
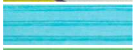
No.	Symbol	Appearance	Number of information assigned	Cartographic means of expression	Haptic variables
1a	Natural lakes		1: type	1: shape	1: shape
1b	Artificial lakes		1: type	1: shape	1: shape
2	Islands	n/a	0	0	0
3	Rivers		1: type	1: line	1: shape
4	River springs		1: type	1: shape	1: shape
5a	Land borders		1: type	2: line, grain	2: shape, grain
5b	River borders		1: type	2: line, grain	2: shape, grain
6	Borders of the neighbouring country		1: type	2: line, grain	1: shape
7	Shorelines		1: type	2: line, grain	1: shape
8	The Baltic Sea		1: type	1: texture	1: texture
9a	Seashore belts		1: type	1: texture	1: texture
9b	Lake districts		1: type	1: texture	1: texture
9c	Lowlands		1: type	1: texture	1: texture
9d	Highlands		1: type	1: texture	1: texture
9e	Valleys		1: type	1: texture	1: texture
9f	Mountains		1: type	1: texture	1: texture
		Total	18	19	18

Table 3. Map symbols and number of information assigned to them – 3D printed map.

No.	Symbol	Appearance	Number of information assigned	Cartographic means of expression	Haptic variables
1	Lakes		1: type	1: shape	1: shape
2	Islands		1: type	1: shape	1: shape
3	Rivers		1: type	1: linie	1: shape
4	River springs	n/a	0	0	0
5	Polish border		1: type	1: line	1: height
6	Borders of the neighbouring country		1: type	2: line, grain	1: shape
7	Shorelines	n/a	0	0	0
8	The Baltic Sea		1: type	1: texture	1: texture
9a	Seashore belts		2: type, height	2: texture, height	2: texture, height
9b	Lake districts		2: type, height	2: texture, height	2: texture, height
9c	Lowlands		2: type, height	2: texture, height	2: texture, height
9d	Highlands		2: type, height	2: texture, height	2: texture, height
9e	Valleys		2: type, height	2: texture, height	2: texture, height
9f	Mountains		2: type, height	2: texture, height	2: texture, height
		Total	18	19	18

Both figures were normalized to the same scale. At first glance, one can see that the 3D printed map is characterized by a higher information value. The pattern of information distribution on both maps is similar. The corners of the maps, which contain little information, have lower information value. The same applies to central regions of Poland, where not much content is presented (this refers to the map of geographical regions).

As comparing the two maps is one of the aims of this paper, Figure 6 presents the differences between values of the 3D map and the original map from the atlas. The biggest differences in this case occur in segments with a higher number of point symbols. This is due to the fact that these cartographic symbols are often highly generalized (displaced) and thus might count for different segments, although they represent the same phenomenon. Besides, as the course of the Polish border coincides on both maps, in these 'bordering segments' the differences are relatively low.

Table 4. Comparison of total values of structural measure of information (SMI) of both maps.

	Original map	3D printed map
Whole map	54.15	61.68
Thematic content	18.69 (35%)	32.70 (53%)
Background content	35.46 (65%)	28.98 (47%)

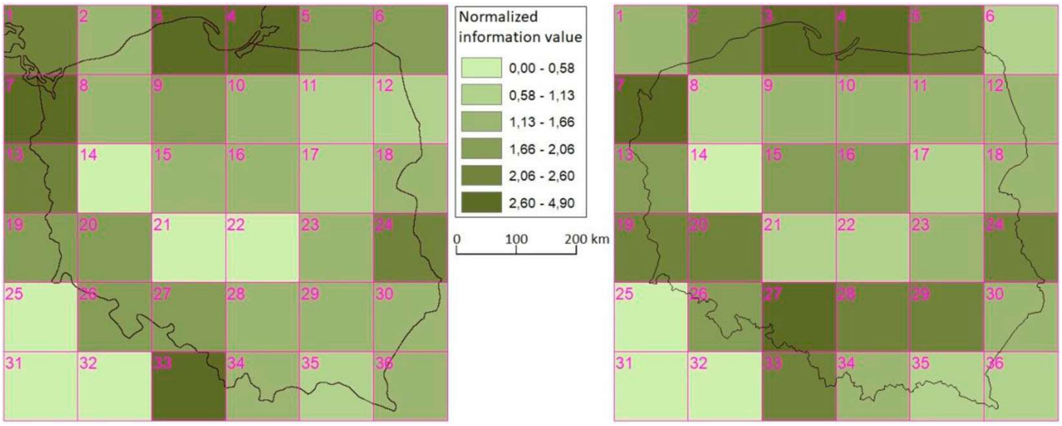


Figure 5. Distribution of the values of structural measure of information. Left – original map from the atlas, right – 3D printed map.

According to the method proposed by Grygorenko (1973), the amount of information assigned to each cartographic symbol on both maps along with the number of cartographic means of expression used to present it were determined. This allowed us to compute the information efficiency coefficient of both maps (W):

- original map from atlas: 0.79
- 3D printed map: 0.95.

At this stage of research, we did not take map inscriptions into account. Only the total number of each type of inscriptions that appears on both maps has been calculated. Table 5 presents the number of each type of inscriptions that appears on both maps.

Discussion

The results allow for a better understanding of importance of the height differentiation of cartographic symbols on tactile maps. It was already established by James (1982) that height differentiation is the best method for hierarchizing map content. Besides, maps on which symbols are put on different heights above the background level are easier to read due to the characteristics of the sense of touch. As a result, the minimum distances between particular symbols at different heights can be reduced (Edman, 1992).

Although these maps were presenting the same geographical phenomenon, they were prepared in different scales and are characterized by slightly different content and level of generalization. Moreover, it is difficult to perform an objective evaluation and comparison of the readability of the two maps examined. The original one from the atlas is commonly used in schools by blind and visually impaired students, while the 3D printed one was only tested by several students (Wabiński, 2017). Students at the Society for the Care of the Blind in Laski (Towarzystwo Opieki nad Ociemniałymi w Laskach, 2019), with which the authors cooperate, are used to work with one of the maps examined (original from the atlas) and find working with it easy, while, at the same time, the 3D printed map is something new and still unknown to them. In the future, it is important to perform tests with volunteers from different societies and schools as well as with different backgrounds to provide a more thorough evaluation of both maps in terms of the cartographic information value they contain. The obtained results can mean, however, that it is still possible to enrich the tactile maps produced in terms of information value, while at the same time, keep them legible.

The results demonstrate that the method of determination of structural measure of information used for traditional maps can also be applied to tactile maps. The only difference is that haptic variables have to be used instead of graphic variables. This constitutes the answer for the third research question and confirms that the methods of map assessment used for classic maps can be adopted to evaluation of tactile maps. This requires some experience in both designing and using these variables to obtain comprehensive information on their basis.

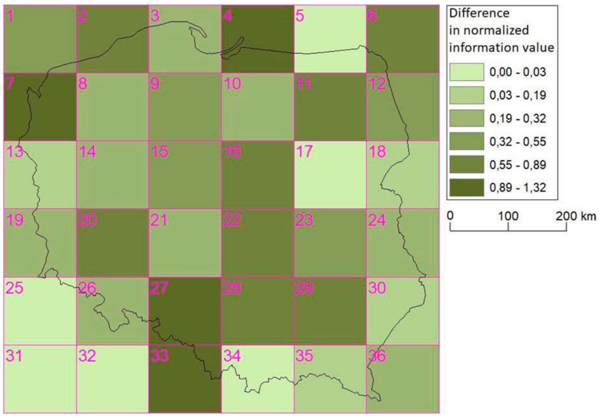


Figure 6. Comparison of information value distribution on both maps.

Table 5. Number of each type of inscriptions used on both maps.

	Map inscriptions	
	Original map	3D printed map
Geographical regions	14	14
Rivers	9	8
Neighbouring countries	0	7
TOTAL	23	29

The information efficiency coefficient of a map is an excellent criterion for assessing the value of a cartographic image. A high value of the coefficient indicates a more rational and economical system of symbols. On the other hand, a low coefficient indicates that the assortment of symbols is not homogenous and that there is superfluous congestion on the map. It also implies that the map contains certain graphic elements that do not carry information. In our research, the information efficiency coefficient of the 3D map was higher (0.95) than on the original map (0.79). Moreover, the coefficient of the 3D map was very close to 1. It means that this map uses a more rational symbol system, close to the optimal solution. It is an advantage of creating a multi-level map, which uses new symbols at varying heights, so that it can provide more information. Besides, there is a positive correlation between the information efficiency coefficient and the structural measure of information of a single map.

3D printing technology is still not perfect and research on its use for tactile map printing requires further development. This production method is relatively slow and requires a good level of expertise to design the 3D model properly. Limitations in terms of the maximum size of printed elements do exist due to the constraints related with construction of modern 3D printers. On the other hand this production method has almost no limitations in terms of the shapes to be created. When combined with low-cost microcontrollers, it can be used for production of interactive maps and small-scale models that are adaptable to various teaching situations, such as education of blind and visually impaired (Giraud *et al.*, 2017). 3D printing was designed for rapid prototyping and is a perfect choice for creation of personalized tactile maps. It can be also used for production of complete tactile atlases.

The selection of material that is pleasing to touch, legible braille inscriptions, patterns readability, 3D symbol design and their coexistence on tactile maps are only few research directions that should be undertaken to work out complete solutions in 3D printed tactile mapping. But the results confirmed our assumptions that the use of 3D printing creates new possibilities in the design of symbols on tactile maps, as well as new challenges. This is possible thanks to differentiation of symbols by means of an additional variable, i.e. height. Further work is needed in this area to develop proposals for new cartographic symbols and thematic tactile maps. It is also important because the cost of 3D printing of one unique map sheet is much cheaper than using traditional printing techniques. This might result in wider access to tactile maps by blind and visually impaired users and also to broaden their applications for other users (Kent, 2019).

Conclusion

The aim of the authors was to establish whether methodologies developed in the past for evaluating a map's information value (e.g. Grygorenko, 1982; Garmiz, 1989; Salistchev, 2002) can also be applied to tactile maps. The results indicate that, after some minor modifications, it is possible to use the methods developed for classic maps to also compute the structural measure of information on tactile maps. Besides, it can be seen that the use of 3D printing, or any other manufacturing technology that allows full freedom in height differentiation of cartographic symbols, makes it possible to increase the information value of a particular tactile map. This kind of analysis may be conducted at the design stage of every tactile map to be produced. This will allow tactile cartographers to design cartographic materials of higher value and to distribute the map content in a more efficient way.

The next step for research in this area is to examine how this methodology might apply to colourful hybrid maps, which are useful for both blind and visually impaired people. According to Salistchev (2002), these methods do not take into account the information that is obtained when analysing the interrelations between certain phenomena presented on the map, and above all, they do not take into account the quality of this information: its accuracy, importance and utility. In case of tactile maps and aids for blind and visually impaired people in general, their utility is the most important factor. Hence, further research should be carried out to analyse how the results can be applied to improve the practical use of maps by blind and visually impaired people.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributor

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RESEARCH ARTICLE

Applying height differentiation of tactile symbols to reduce the minimum horizontal distances between them on tactile maps

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Abstract

In this paper, we wanted to verify the hypothesis that extruding cartographic symbols on tactile maps to different heights might allow reducing the minimum (suggested in the literature) horizontal distances between them, without impacting the overall map's legibility. This approach might allow preparing tactile maps in smaller scales and thus, reducing production cost, or putting additional spatial information on the same map sheet that would not fit otherwise. To verify the hypothesis we have prepared 6 different stimuli variants with or without height differentiation applied and different horizontal distances between tactile symbols adopted (1 mm, 2 mm and 3 mm). In the controlled study sessions with 30 participants with visual impairments we have measured the times required for solving 3 different spatial tasks on 3D printed tactile stimuli. We have also performed qualitative analysis to learn participants' opinions about the proposed design and materials used. It turns out that applying height differentiation not only results in shorter times required for solving spatial tasks but is also considered by blind individuals as a convenient improvement in terms of use comfort and allows reduction of recommended minimum horizontal distances between symbols on tactile maps.

Introduction

A growing number of maps being produced is connected with the increasing demand for information provided in a very concise and convenient way, available for quick assimilation. These conditions, undoubtedly, are fulfilled by using cartographic form that shows spatial relations in a direct way, as a reflection of these relations in reality [1]. However, not many of the maps produced are of truly high quality. Besides, the vast majority of modern maps are digital, and thus, usually unavailable for people with special needs, such as people with visual impairment (PVI). This results in a situation, where access to high-quality tactile maps is incomparably more difficult than to their classic counterparts.

Consequently, students with visual impairments have difficulties with understanding of the maps. Most tactile maps are available in Braille textbooks or atlases, but are prepared using

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inappropriate techniques, e.g. Tiger embosser that is not efficient in differentiating tactile symbols [2]. Too high complexity of tactile graphics is the main factor lowering their comprehensibility by PVI (e.g. adaptation of too detailed maps without proper generalization). Thus, preparing them while using a production technique that increases the sense of complexity and is tactilely unfriendly is an inefficient strategy. As a result, almost 47% of blind students are unable to follow their peers with normal vision when solving tasks in a class [3].

Other than that, it turns out that students who learned a given area by scanning tactile maps were considerably more proficient in unguided route following than those who based on direct experience or verbal instructions [4].

But why are not digital maps converted into tactile form, legible by PVI? Tactile map development is complicated and expensive. They often require personalization–either due to the needs of a reader or because they are supposed to map specific areas or even routes. Tactile maps also require a decent level of generalization because of the way PVI perceive maps—using their sense of touch or damaged sight. Not only is the resolution of a finger approximately 10 times worse than that of an eye (in normal conditions), but also tactile maps are usually being read fragment by fragment, out of which an image of the whole map is built up in a reader's memory [5]. This makes the production of tactile maps complicated and difficult to automate. A number of solutions for automatic tactile map generation have been proposed but none of them can be treated as a holistic solution that meets all the requirements of PVI [6]. Moreover, many of the commonly used production methods (e.g. thermoforming or relief screen printing) are cost-effective only in the case of mass production, whereas tactile maps usually have to be printed in small quantities.

The amount of information conveyed by each map depends on the number and type of elements used on it, as well as on cartographic symbols used for presentation [7]. Due to the need of strong generalization of map elements that includes sparse arrangement of tactile symbols, allowing PVI to read them, it is not possible to fit the same number of cartographic symbols on a tactile map as on its classic counterpart. It is important to develop new solutions that could allow compacting tactile map content or increasing the amount of information of single tactile symbols. Unfortunately, both are hard to achieve due to the perceptive limitations of PVI.

When creating tactile equivalents of classic maps, a number of solutions can be used to convey the same amount of information. Tactile counterparts can be for example prepared in larger formats. But limitations in terms of maximum dimensions of a tactile map sheet do exist–a seated reader has to cover the whole sheet with his/her arms [8]. Another possibility is to create a series of maps of the same area, each of them covering only a part of the topic [9]. This solution, however, is more expensive and time consuming. An alternative is to try to increase the information value of a particular tactile map or its legibility. On classic maps this can be achieved by using various graphic variables that facilitate distinguishing cartographic symbols. Unfortunately, when designing maps to be read using touch, cartographers cannot use variables based on colour–the ones that are the easiest to perceive [10]. Instead, they are limited to a set of haptic variables [11] (Fig 1).

Most haptic variables are already widely used on tactile maps and it is difficult to find their further differentiation possibilities. The variable that seems to have potential in this matter is height. This is because the hitherto used methods of tactile maps printing make it possible to print symbols of the varying height only to some limited extent. But even though it is possible, not many tactile maps offer height differentiation of cartographic symbols. The emerging new production techniques, such as 3D printing, make it possible to print almost any symbols and thus, to freely differentiate their heights.

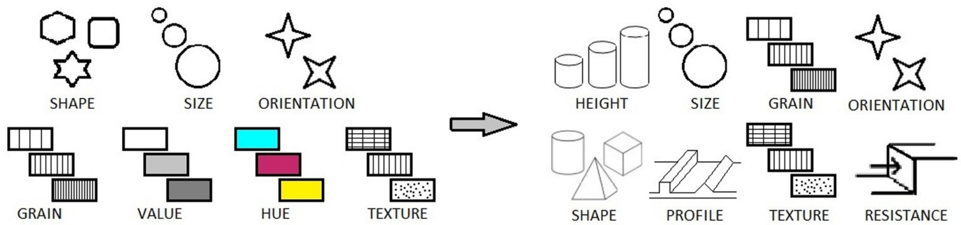

Fig 1. Graphic and haptic variables, source: Based on [11].

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Information conveyed by tactile maps

The information value of a map is influenced not only by the number of content elements present on a given map fragment (e.g. 1 cm^2), but also the amount of information transmitted by individual symbols and the structure of their arrangement on a given map fragment [12, 13]. New tactile map design principles together with the new editorial rules should be developed to increase tactile maps' information values, while still keeping them legible. We have already proven that introducing height differentiation of symbols on a tactile map leads to the increase of information value [11].

The importance of this concept has been widely discussed in the literature. One of the methods to partly eliminate clutter on tactile maps is to use height differentiation of tactile symbols [14, 15]. Maps with different cartographic symbols, varying in heights from the background material, are easier to read and understand [9]. A more recent study showed a strong user preference towards 3D plans in favour of 2.5D tactile graphics [16].

Design requirements for tactile maps

Tactile maps design guidelines in many countries suggest minimum distances to be kept between tactile symbols in order to maintain map's legibility. The most commonly quoted value in the literature on this subject is 3 mm [17–19], which is related with an average resolution of a finger, estimated to be between 2.4 and 3 mm [20]. This distance is sufficient in case of two highly contrasting symbols. In order to distinguish two symbols placed next to each other that are similar in shape or smaller in size than suggested in literature, this distance should be increased to 5–6 mm [17].

Taking the above into consideration, we would like to analyse the impact of tactile symbols height differentiation and related new editorial proposals on the amount of information conveyed by tactile maps. Therefore, **the aim of this study was to examine whether the height differentiation of tactile symbols enables reduction of horizontal distances between them, while maintaining legibility of a tactile map**. We assumed that applying height differentiation improves the legibility of maps. We defined the hypothesis that height differentiation of tactile symbols also allows the reduction of suggested in literature distances between particular symbols. **We would like to determine to what extent these distances can be reduced, if at all.** Our hypothesis was that height differentiation of symbols on tactile maps may either allow an increase of the number of cartographic symbols used (thereby, real-world elements presented) on a single map, while still keeping it legible or, to a decrease of map scale as well as map sheet dimensions and thus, the related expenses. We also assumed that in such case less generalization could be applied and thanks to that, real-world objects could be represented on tactile maps more realistically and with less distortions. This is especially important in case of elements, whose location and/or size have to be precisely rendered. Such solutions will finally increase the information value of a particular map.

Therefore, the following research questions were defined:

RQ1: Does height differentiation of cartographic symbols on tactile maps allow reduction of recommended minimum distances between them?

RQ2: To what extent can minimum horizontal distances between particular symbols be reduced for symbols with varying heights?

RQ3: Do height differentiation of cartographic symbols and reduction of minimum distances between them increase information value of tactile maps?

Our findings can lead to more efficient tactile map production and facilitate the process of their development, including automatic generalization. As a consequence, this may contribute to reduction of the costs of tactile maps production.

Materials and methods

We have divided our research into three stages: (1) developing tactile stimuli, (2) human subject testing along with statistical analysis of the results, and (3) information value evaluation. Each of these stages is described in the following subsections.

Developing tactile stimuli

To verify our hypothesis we had to design a set of tactile stimuli that would mimic tactile maps. These *pseudomaps* [as referred in 19] were not based on any particular spatial data but were purposely designed for this research. Their design was supposed to allow performing simple spatial tasks evaluating the potential of tactile symbols' height differentiation. For this purpose we have prepared a number of variants of the same tactile stimulus. We have chosen 3 levels of complexity, defined by the minimum horizontal distances between symbols to be kept. For each level of complexity, we have designed 2 stimulus versions: with and without height differentiation.

We used the versions without height differentiation (D1, D2, D3 in Fig 2) to examine the effect of the minimum horizontal distances reduction on the map readability. These stimuli variants also constituted a reference data for examining the impact of height differentiation of

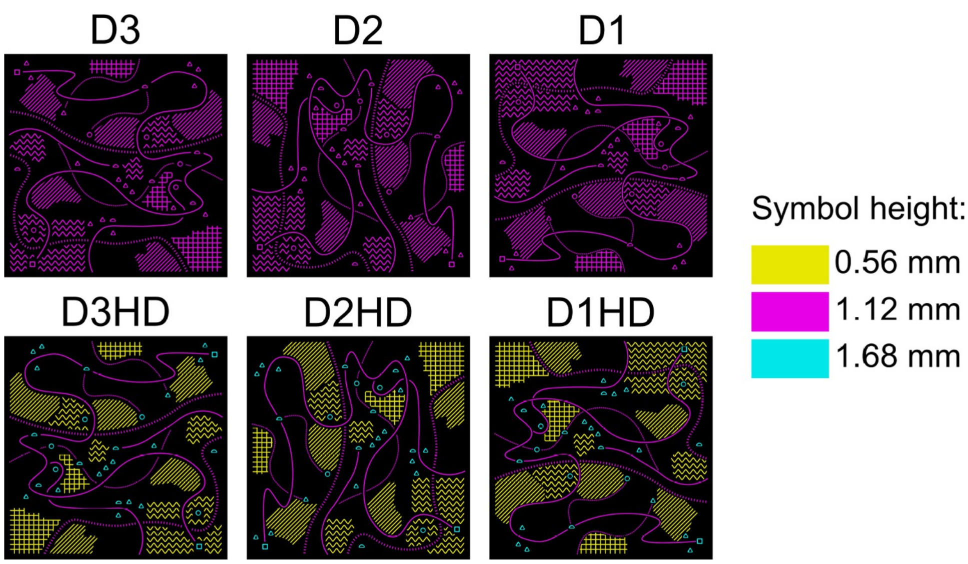

Fig 2. The stimuli used in our study. Different colours indicate heights of particular symbol types. Mirroring and rotations are visible.

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symbols on the map readability–to find answer to the RQ1. We used the variants with height differentiation applied (D1HD, D2HD, D3HD in Fig 2) to test to what extent the spacing between the symbols could be reduced, providing answer to the RQ2.

In order to minimize potential confounding variables, we have prepared 7 different versions of alignment of the symbols on particular stimuli, so that none of the variants has the same arrangement of symbols. By applying rotations and mirror reflections we wanted to avoid participants' memorization of specific patterns on the stimuli, while repeating tasks. We presented the stimuli variants to the participants in random order.

We have maintained the same number of symbols on each stimuli that allowed us to eliminate potential confounding variables in the form of modified number or character of tactile symbols used. We have also prepared an extra "pilot" stimuli that was presented to participants first so that they could get familiar with the maps' content and their legend. This additional stimuli version was not used in the performance analysis. The universal legend was printed separately. We have glued the 3D printed symbol list to a swell-paper sheet with Braille descriptions.

As it was confirmed in one of our previous studies [21], the minimum distances of 3 mm between contrasting tactile symbols are sufficient for 3D printed tactile maps to be read correctly. In this research we wanted to verify if it is possible to further reduce these distances, while still being able to solve spatial tasks. The proposed stimuli variants were prepared as described in Table 1. Each of the stimuli variants has its own stimulus code, e.g. D3HD stands for 3 mm minimum horizontal distances between symbols with height differentiation applied, whereas for D1 variant 1 mm of minimum horizontal distances were applied with all symbols put at the same height. Visual representation of the stimuli variants used in our study is presented in Fig 2.

Applying mirror reflections causes some of the area symbol textures (in orange–Fig 3) to change their orientation. We have modified these area symbols to keep their orientation the same across every stimuli but without altering their outlines that were used for information value calculations. This operation had no impact on symbols outlines but resulted in slightly different numbers of elements and their arrangement within outlines.

In future tasks related with production of tactile maps, the reduction of minimum distances between particular tactile symbols could allow placing more symbols of any type on the same map sheet, or to more realistically depict the real-world objects (e.g. their borders or outlines). In this research, the number of symbols remained the same across all the stimuli, in order not to introduce potential confounding variables. Instead of introducing new tactile symbols, we used the additional space gained after reducing the minimum distances and filled them with symbols already existent on stimuli (Fig 4).

Table 1. Tactile stimuli variants.

Stimulus code	Complexity level: minimum distances	Height differentiation [mm]	Rotation	Mirror reflection
D3	Low: 3 mm	No (1.12)	0˚	Yes
D2	Medium: 2 mm	No (1.12)	270˚	No
D1	High: 1 mm	No (1.12)	180˚	No
D3HD	Low: 3 mm	Yes (0.56, 1.12, 1.68)	0˚	No
D2HD	Medium: 2 mm	Yes (0.56, 1.12, 1.68)	270˚	Yes
D1HD	High: 1 mm	Yes (0.56, 1.12, 1.68)	180˚	Yes
Pilot [a]	varies	Yes (varied)	90	No

[a] not considered in the performance analysis

https://doi.org/10.1371/journal.pone.0264564.t001

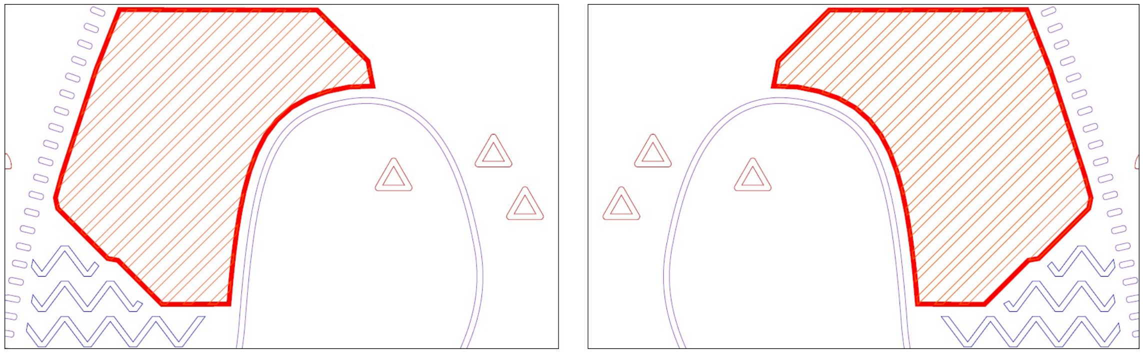

Fig 3. The impact of mirror reflection on area symbol texture.

https://doi.org/10.1371/journal.pone.0264564.g003

The knowledge and good practices regarding the design of symbols on classic maps cannot be directly applied as a guide for production of tactile symbols [22]. Even though the standardization of tactile symbols has not yet been fully achieved [23], some guidelines and good case examples on how to design tactile maps and symbols on them do exist [e.g. 17, 18]. Based on these guidelines and our past experience with 3D printed tactile maps [11] we have carefully selected tactile symbols to be used on the stimuli. Our aim was to select the symbols that are commonly used on tactile maps, especially the 3D printed ones (cf. Table 2). We have chosen easily distinguishable symbols that were used together on particular map sheets in past research and are well known to PVI. By doing this, we wanted to remove potential confounding variables and evaluate only the impact of height differentiation and minimum distances between particular symbols.

The extrusion heights of particular symbols categories are based on past experiments [14, 21]. The larger the symbol, the less extrusion it requires. Thus, the biggest extrusion has been applied to point symbols (1.68 mm). Line symbols have been extruded to 1.12 mm height, whereas area symbols are 0.56 mm in height. On stimuli variants with no height differentiation applied, a fixed height of 1.12 mm was used for every tactile symbol. These values are a multiple of selected layer thickness of 3D printing process (0.14 mm).

According to the report of the National Federation of the Blind [32], only 10% of 1.3 million legally blind people in the United States are Braille readers. Today, children with visual impairments express strong preference for audio materials instead of Braille publications–Braille on paper is declining in Europe [33]. For this reason we resigned from placing Braille labels on

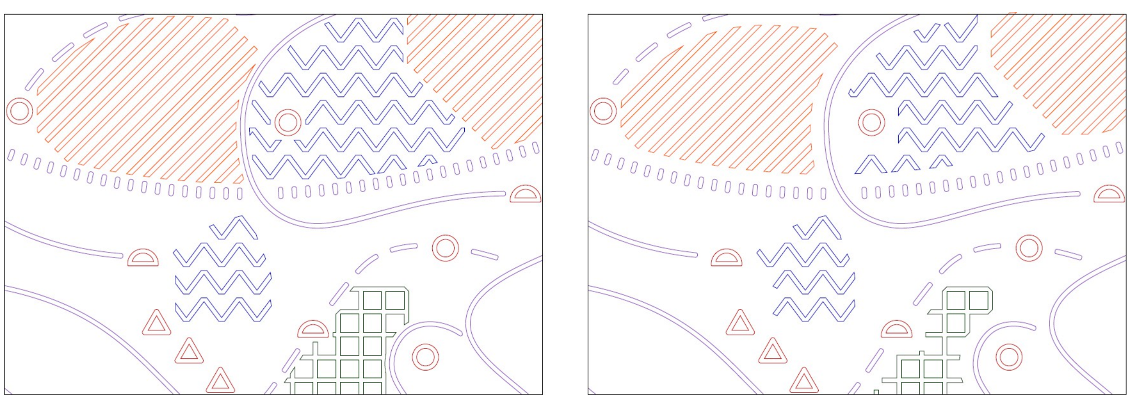

Fig 4. The increase of free space that can be filled with tactile symbols when reducing minimum distances between symbols.

https://doi.org/10.1371/journal.pone.0264564.g004

Table 2. The symbols used in the research.

POINT SYMBOLS				
CONTOUR WIDTH: 1 MM, EXTRUSION HEIGHT: 1.68 MM				
SYMBOL GEOMETRY	**Dimensions [mm]**	**Referenced in**	**Purpose of use**	**Accompanying symbols**
TRIANGLE	length: 6.25 width: 5.5	[24]	n/a	zig-zag, check pattern, line pattern, solid line
		[25]	point of interest	circle, square, solid line
CIRCLE	diameter: 5.75	[9][a]	junction of paths	solid line, dashed line
		[26]	telephone booth	line pattern
		[25]	point of interest	triangle, square, solid line
SQUARE	length: 5.75	[27][b]	telephone booth	solid line, dashed line, pattern line
		[25]	point of interest	triangle, circle, solid line
HALF ELLIPSE	length: 6.75	[21]	lake	solid line, zig-zag, line pattern
	width: 3.75	[28][c]	lake	circle, solid line, zig-zag, line pattern
SYMBOL GEOMETRY	**Dimensions [mm]**	**Referenced in**	**Purpose of use**	**Accompanying symbols**
SOLID LINE	line width: 1	[24]	n/a	triangle, zig-zag, check pattern, dashed line
		[27][b]	main road	square, dashed line
		[21]	river	half ellipse, zig-zag, line pattern
DASHED LINE	line width: 0.5 dash thickness: 0.5	[27][b]	railway	square, solid line
	dash width: 1.5 gap: 1.5	[24]	n/a	triangle, zig-zag, check pattern, solid line
PATTERN LINE	dash thickness: 1 dash width: 2.5	[29][a]	fence	circle, solid line, dashed line
	gap: 2	[30]	tramway	solid line
SYMBOL GEOMETRY	**Dimensions [mm]**	**Referenced in**	**Purpose of use**	**Accompanying symbols**
ZIG-ZAG	line width: 1	[17][a]	recommended texture	can be used with any textures (universal)
	vert. dist.: 6	[31]	n/a	triangle, check pattern, solid line, dashed line
	horiz. dist.: 7.75	[21]	mountains	half ellipse, solid line, zig-zag, line pattern
CHECK PATTERN	line width: 1 vertical dist.: 5	[17][a]	recommended texture	can be used with any textures (universal)
	horizontal dist.: 5	[31]	n/a	triangle, solid line, dashed line, zig-zag, line pattern
LINE PATTERN	line width: 1 vert. dist.: 4.25	[26]	green area	circle
	horiz. dist.: 4.25	[21]	highlands	half ellipse, solid line, zig-zag
	angle: 45°/225°	[17][a]	recommended texture	can be used with any textures (universal)

Other than 3D printing

[a] Microcapsule method (swell paper)

[b] Manual methods

[c] Thermoforming method

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the stimuli. We did not want to limit study participants only to those who can read Braille. Braille descriptions were only placed on a map legend but the researchers offered their help in case participants were not able to read the descriptions.

We have decided to use a 3D printing method for stimuli production, and more specifically–Fused Deposition Modelling (FDM). This method uses thermoplastic material to form a physical model layer by layer on the 3D printer's surface. We have chosen this production method due to its characteristics and applicability in tactile aids production [e.g. 34–36]. 3D printing is perfect for rapid prototyping and thus, new map designs can be verified at fast pace and at low cost.

Human subject testing

In order to verify our hypothesis, we have planned a research activity that involved human testing of PVI both congenitally/early (under 5 years old) and adventitiously blind. Participants were asked to solve a number of basic location tasks using tactile map stimuli, designed for this particular research. Every participant had to repeat three location tasks on each stimulus variant (18 tasks total). Every task was related with different geometry type of cartographic symbols:

- Task 1—locate 5 point symbols on the map of a given type (the reference symbol to be found was shown to participants before the actual task on map legend).
- Task 2—locate 5 area symbols in the same manner.
- Task 3—follow the path (line symbol) to the specific point from their current location (indicated at the start by a researcher), while avoiding obstacles (both in a form of area and point symbols).

By asking participants to solve similar spatial tasks on different variants of the same tactile stimuli, we have verified the impact of different approaches of height differentiation and placement of tactile symbols on their overall performance. Each participant, prior to performing the designed tasks, was allowed to examine the pilot map (stimulus) and the associated legend briefly–explore its dimensions and material used as well as the symbols used.

The recruitment process for the study was carried out by the authors with help of the Polish Blind Association (https://pzn.org.pl/). People willing to take part in our research study were asked to indicate their interest through a web-based response form. The recruitment forms were prepared in accordance with the Research Protocol (S1 File). Before conducting the actual recruitment phase, we have tested the research procedure in a pilot study with 2 PVI.

Every participant was examined individually. We were documenting their performance of solving the tasks (time required) as well as their behaviour during that process by recording their body movement on video. After sessions, participants were asked to answer a number of questions to get participants' feedback (qualitative analysis). Each participant took part in one session lasting approximately 60 minutes. The tests were conducted according to the previously established schedule described in the Research Protocol.

The performance results and answers from the questionnaires were later anonymously aggregated and analysed using statistical measures.

To confirm our hypothesis and answer RQ1 and RQ2 all variants of the stimuli were necessary. Stimuli with all the symbols extruded to the same height served as the reference for stimuli with height differentiation applied. Comparison of stimuli with and without height differentiation was a key point to determine what kind of changes we obtain thanks to this design modification (RQ1). Comparison of stimuli with height differentiation was necessary to measure the impact of these changes (RQ2). Therefore, all the performance results were included in the statistical analyses.

We have used non-parametric versions of all the statistical tests as our data do not meet the assumptions of parametric tests, such as normal sampling distribution (result of Kolmogorov-Smirnov test was of statistical significance, $p<0.05$). To analyse our data, we have conducted an overall Friedman rank sum test (for repeated measures of our respondents solving task in six stimuli variants), Kruskal-Wallis test (independent samples for two or more groups) and the Mann-Whitney U test (for two independent groups) to see if there were any significant differences in the measured variables among the various conditions. For the Friedman rank sum test, we performed a pairwise Wilcoxon signed rank test as the post hoc test, with a Benjamini-Hochberg (BF) correction. We followed the Kruskal-Wallis tests with a Dunn's post hoc test along with Benjamini-Hochberg correction, where we compared specific pairs. Data were analysed using IBM Statistics 27.

Information value evaluation

We have also examined the influence of cartographic symbols' height differentiation and their arrangement on the overall information value of the tactile stimuli prepared. One of measures that defines the informational potential of a map is structural measure of information, first proposed by Salistchev [7]. The structural measure of information was used for evaluation of tactile maps in one of our past research [11]. Due to the fact that in this research only simple tactile stimuli were used (rather than regular tactile maps), we had to modify the original formula for measuring structural measure of information. The weights applied to particular symbol types are the same—each symbol defines only location and real-world object category:

$$SMI = \sum_{i=1}^{k} a_i + \sum_{i=1}^{l} b_i + \sum_{i=1}^{m} c_i \quad (1)$$

where k, l, m is the number of point, line and area cartographic symbols of a given type, a_i is the number of point symbols of particular type, b_i and c_i are respectively: the lengths of particular types of linear symbols and boundary lines of area symbols.

It is not possible to compare the measurements for particular symbol types directly, due to significant differences in the measured values between different geometries. Point symbols are counted one by one, whereas for line and area symbols, geometrical measures are used. Using normalization in that case was impossible, as the number of point symbols on each stimulus is the same. For this reason we have decided to examine only the geometrical measures of line and area symbols to determine the potential increase of information value, when reducing the minimal distances between tactile symbols.

Results

The resulting stimuli are 22 by 22 cm in planar size (Fig 5). We used real-scale vector drawings for the geometrical measurements that determine the potential increase of information value.

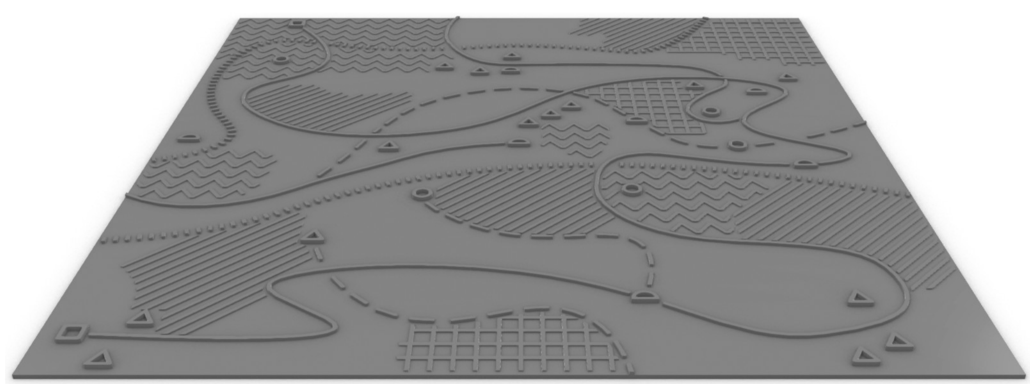

Fig 5. Digital 3D Model of one of the stimuli variants.

https://doi.org/10.1371/journal.pone.0264564.g005

Two exemplary vector drawings of the stimuli with 3 mm offsets around every symbol are presented in Fig 6. In this case a mirror reflection has been used for differentiation and to prevent the map content from being memorized.

The stimulus base thickness was set to 1.2 mm. We have proven during the pilot study that this thickness provides sufficient durability of the material. We have prepared 7 physical variants of the 3D stimuli, using PLA material. In order to provide an element for stimuli orientation, specially designed convex triangles were 3D printed and then glued to the upper right corner of each stimulus.

Testing phase

The testing phase was conducted at the Polish Blind Association building in Warsaw, Poland. It lasted for 3 days in May 2021. Out of over 50 applicants, we have selected a group of 30 people (aged 16–65) that took part in our study. The number of participants examined allowed us to avoid potential confounds related to the repetition of location tasks on a number of variants of the same map by a single reader (Fig 7).

Based on the application forms, we have tried to choose the most representative group (statistically diverse). We recruited 16 male and 14 female participants, the mean age was 38.9 (SD = 10.45). Most of them (22) were congenitally blind or lost their sight before 5 years old (early blind), whereas 7 persons had adventitious blindness (1 participant did not provide the moment of sight loss). The majority had high (12 individuals) or average experience (16) of using tactile maps according to their subjective assessment and high (23) or average experience (7) with Braille reading.

No statistically significant differences were noted between level of experience with tactile maps and Braille reading (Mann-Whitney U-test $\chi^2(3) = 1.815$, $p = 0.612$). Early blind participants had higher level of experience with Braille reading than adventitiously blind ($\chi^2(1) = 10.881$, $p<0.05$, mean rank value for early blind: 17.18; mean rank value for adventitiously blind: 8.14), but there was no statistically significant difference in level of experience with tactile maps between early blind and adventitiously blind participants ($\chi^2(1) = 0.270$, $p = 0.603$). The characteristics of the participants of our study are presented in Fig 8.

Performance results

The main goal of the testing phase was to evaluate times required for solving the 3 spatial tasks. We assumed that the lower the average times needed to solve spatial tasks by the study participants, the more legible the particular tactile stimuli are. This means that the tactile stimuli

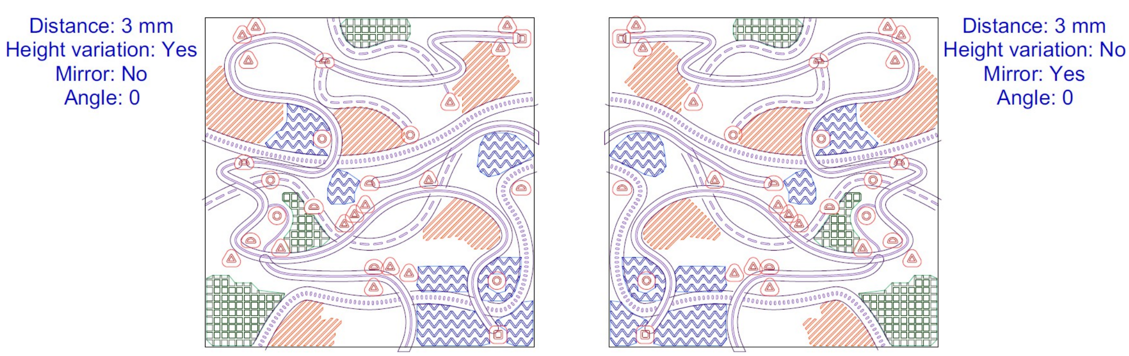

Fig 6. A pair of vector drawings used for geometric calculations. The applied 3 mm offsets are visible.

https://doi.org/10.1371/journal.pone.0264564.g006

Fig 7. One of the study participants during the testing phase, source: Own photo.

https://doi.org/10.1371/journal.pone.0264564.g007

variants with the lowest mean solving times and highest solved tasks rate are considered the best cartographic design options.

The maximum time available for solving a task was set to 5 minutes. If, after this time, the task remained unsolved, we informed the participants about this fact and moved onto the next tasks and/or stimulus variant. To determine average solving times of particular tasks, the unsolved ones were excluded to count real average solving time. Based on our observations, the first stimulus presented was usually characterized by slightly longer solving times than average for that stimulus variant but we avoided its impact by presenting particular variants to the study participants in random order.

The results of Mann-Whitney U test showed no significant differences in the average solving times for each stimulus variant and each task among congenitally/early and adventitiously blind study participants. Moreover, Kruskal-Wallis test showed no statistically significant differences between participants' level of experience with tactile maps or Braille reading and the average tasks solving times.

When it comes to finding point symbols (small elements) on tactile maps (task 1), the lack of height differentiation of the symbols directly affects the readability of the map (Tables 3–5). Decreasing the minimum distances between symbols to 1 mm made identification of the symbols impossible (93.3% of study participants). Reducing this distance to 2 mm gave a positive

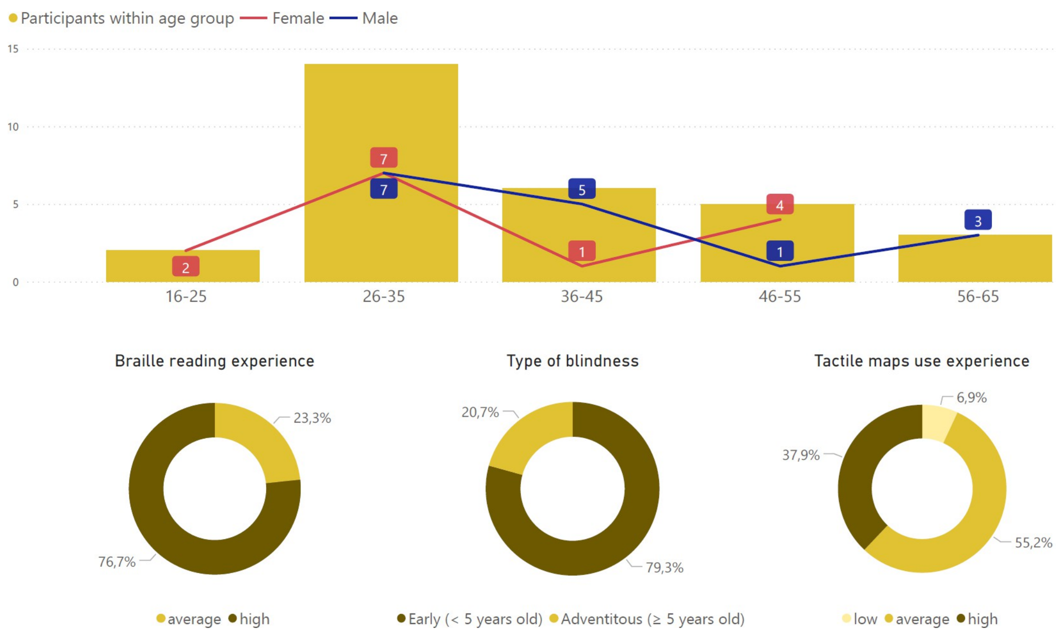

Fig 8. Study group statistics.

https://doi.org/10.1371/journal.pone.0264564.g008

result only in 36.7% of cases, and to 3 mm—in 56.7% of cases. However, with height differentiation applied, the study participants were able to find and identify point symbols in 96.7% of cases, regardless of the distance between the elements. Table 3 shows the average solving times for each stimulus variant, including only those cases which were successfully completed. In the analyses of significance of differences, the D1 variant was excluded because the number of valid observations was less than 5 (2 cases).

The Friedman test result showed statistically significant differences between solving times of stimuli variants ($\chi^2(4) = 13.400$; $p < 0.05$). Pairwise Wilcoxon Signed-Rank tests with a BH correction let us detect that no statistically significant differences were found between the time of correct identification of the symbols and the minimal distances between them for stimuli variants with height differentiation applied (Tables 4 and 5). These variants are feasible and we can observe lower average solving times in comparison to variants without height differentiation.

For task 1, in the case of using the same distances between symbols, but above 1 mm, the height differentiation significantly impacts the time of symbol identification. For D2HD-D2

Table 3. Task 1 statistics.

STIMULUS CODE		D1	D2	D3	D1HD	D2HD	D3HD
N	Valid	2	11	17	29	29	29
	Missing	28	19	13	1	1	1
MEAN		02:45	03:12	02:41	01:43	01:40	02:07
MODE		02:15	04:59	00:43[a]	01:15[a]	01:28[a]	02:15
STD. DEVIATION		00:42	01:17	01:29	01:01	01:05	01:16
MINIMUM		02:15	01:18	00:43	00:31	00:32	00:33
MAXIMUM		03:15	04:59	04:56	04:38	05:00	04:59

[a] Multiple modes exist. The lowest value is shown

https://doi.org/10.1371/journal.pone.0264564.t003

Table 4. Wilcoxon signed ranks test—task 1.

STIMULI PAIR (CODES)	D3-D2	D1HD-D2	D2HD-D2	D3HD-D2	D1HD-D3
Z	-1.540[a]	-2.401[a]	-2.936[a]	-2.312[a]	-1.888[a]
ASYMP. SIG. (2-TAILED)	.123	.016	.003	.021	.059
STIMULI PAIR (CODES)	D2HD-D3	D3HD-D3	D2HD-D1HD	D3HD-D1HD	D3HD-D2HD
Z	-1.939[a]	-2.017[a]	-.384[a]	-.854[b]	-1.754[b]
ASYMP. SIG. (2-TAILED)	.052	.044	.701	.393	.079

[a] based on positive ranks

[b] based on negative ranks

https://doi.org/10.1371/journal.pone.0264564.t004

Table 5. Task 1 –ranks.

STIMULI PAIR (CODES)		N	MEAN RANK	SUM OF RANKS
D3-D2	Negative Ranks	7[a]	4.14	29.00
	Positive Ranks	1[b]	7.00	7.00
	Ties	0[c]		
	Total	8		
D1HD-D2	Negative Ranks	10[d]	6.00	60.00
	Positive Ranks	1[e]	6.00	6.00
	Ties	0[f]		
	Total	11		
D2HD-D2	Negative Ranks	11[g]	6.00	66.00
	Positive Ranks	0[h]	.00	.00
	Ties	0[i]		
	Total	11		
D3HD-D2	Negative Ranks	10[j]	5.90	59.00
	Positive Ranks	1[k]	7.00	7.00
	Ties	0[l]		
	Total	11		
D1HD-D3	Negative Ranks	11[m]	9.50	104.50
	Positive Ranks	5[n]	6.30	31.50
	Ties	1[o]		
	Total	17		
D2HD-D3	Negative Ranks	11[p]	9.59	105.50
	Positive Ranks	5[q]	6.10	30.50
	Ties	0[r]		
	Total	16		
D3HD-D3	Negative Ranks	13[s]	8.23	107.00
	Positive Ranks	3[t]	9.67	29.00
	Ties	1[u]		
	Total	17		
D2HD-D1HD	Negative Ranks	13[v]	15.77	205.00
	Positive Ranks	14[w]	12.36	173.00
	Ties	0[x]		
	Total	27		

(*Continued*)

Table 5. (Continued)

STIMULI PAIR (CODES)		N	MEAN RANK	SUM OF RANKS
D3HD-D1HD	Negative Ranks	13[y]	12.73	165.50
	Positive Ranks	15[z]	16.03	240.50
	Ties	0[aa]		
	Total	28		
D3HD-D2HD	Negative Ranks	10[ab]	11.60	116.00
	Positive Ranks	17[ac]	15.41	262.00
	Ties	0[ad]		
	Total	27		

a. D3 < D2
b. D3 > D2
c. D3 = D2
d. D1HD < D2
e. D1HD > D2
f. D1HD = D2
g. D2HD < D2
h. D2HD > D2
i. D2HD = D2
j. D3HD < D2
k. D3HD > D2
l. D3HD = D2
m. D1HD < D3
n. D1HD > D3
o. D1HD = D3
p. D2HD < D3
q. D2HD > D3
r. D2HD = D3
s. D3HD < D3
t. D3HD > D3
u. D3HD = D3
v. D2HD < D1HD
w. D2HD > D1HD
x. D2HD = D1HD
y. D3HD < D1HD
z. D3HD > D1HD
aa. D3HD = D1HD
ab. D3HD < D2HD
ac. D3HD > D2HD
ad. D3HD = D2HD

https://doi.org/10.1371/journal.pone.0264564.t005

stimuli pair ($Z = 2.017$; $p<0.05$), D2HD average solving time was faster by 1:32 than D2. In case of D3HD-D3 ($Z = 2.017$; $p <0.05$) by 0:34. The study has also demonstrated other significant differences between variants. For the stimuli pair D1HD-D2 ($Z = 2.401$; $p<0.05$), D1HD average solving time was faster by 1:28 than D2. In the case of D3HD-D2 pair ($Z = 2.312$; $p<0.05$), by 1:05. Comparison of solving times for D3, D2HD and D1HD showed trend towards significance: D2HD average solving time was lower by 01:01 than D3 ($Z = 1.888$; $p = 0.059$) and D1HD on average lower by 0:58 than D3 ($Z = 1.939$; $p = 0.052$).

Table 6. Task 2 statistics.

STIMULUS CODE		D1	D2	D3	D1HD	D2HD	D3HD
N	Valid	30	30	30	30	30	30
	Missing	0	0	0	0	0	0
MEAN		00:27	00:21	00:22	00:28	00:22	00:24
MODE		00:20	00:14[a]	00:16	00:12[a]	00:10	00:16[a]
STD. DEVIATION		00:18	00:17	00:11	00:36	00:15	00:12
MINIMUM		00:04	00:06	00:05	00:07	00:09	00:05
MAXIMUM		01:19	01:25	00:53	03:16	01:13	01:01

[a] Multiple modes exist. The lowest value is shown

https://doi.org/10.1371/journal.pone.0264564.t006

In conclusion, in case of point symbols, using height differentiation, while reducing distances between symbols, improves the identification process of point symbols in relation to the variants with larger distances between the symbols without height differentiation.

The second task that required identification of large area symbols was fairly easy for all the participants and the average solving times were almost the same across all the stimuli variants that we analysed (21–28 seconds: Table 6). The differences between times of identification of area symbols in stimuli variants are not statistically significant (Friedman's test $\chi^2(5) = 7.294$; $p > 0.05$). The times required for solving this task depended more on the scanning technique used than the way the particular stimulus was designed.

The third spatial task required the readers to track a path from starting point to the goal. To make things harder, the goal was hidden in the heights (zig-zag pattern). Thus, we can observe the impact of both increased minimum distances and height differentiation applied on the average results. For most participants (76.6%), solving this task on the D1 stimulus variant was impossible (cf. Tables 7–9). For all other samples we can observe slightly lower average solving times for stimuli variants with height differentiation applied (D1HD, D2HD, D3HD). The differences in the times of identification of line symbols were statistically significant (Friedman's test $\chi^2(4) = 18{,}554$; $p<0.05$).

According to the results of pairwise Wilcoxon Signed-Rank tests with a BH correction (Tables 8 and 9), tracking the path (line symbols) was the most effective when participants used stimuli variants with height differentiation applied (average solving time for D3HD: 00:29). Moreover, there were significant differences between average solving times for D3HD in comparison with D2HD and D1HD: 00:12 ($Z = 3.557$; $p<0.05$) and 00:41 ($Z = 3.929$; $p<0.05$) respectively. Differences between D1HD and D2HD in solving times were not statistically significant.

Table 7. Task 3 statistics.

STIMULUS CODE		D1	D2	D3	D1HD	D2HD	D3HD
N	Valid	7	30	30	30	30	30
	Missing	23	0	0	0	0	0
MEAN		02:40	01:04	00:47	00:42	00:41	00:29
MODE		00:55[a]	00:29	00:30	00:19	00:23	00:15
STD. DEVIATION		01:24	01:10	00:48	00:28	00:35	00:19
MINIMUM		00:55	00:20	00:15	00:14	00:10	00:13
MAXIMUM		05:00	04:52	03:45	02:14	02:34	01:26

[a] Multiple modes exist. The lowest value is shown

https://doi.org/10.1371/journal.pone.0264564.t007

Table 8. Wilcoxon signed ranks test—task 3.

STIMULI PAIR (CODES)	D2-D1	D3-D1	D1HD-D1	D2HD-D1	D3HD-D1	D3-D2	D1HD-D2	D2HD-D2
Z	-2.371[b]	-1.859[b]	-2.366[b]	-2.371[b]	-2.366[b]	-2.356[b]	-.946[b]	-2.271[b]
ASYMP. SIG. (2-TAILED)	.018	.063	.018	.018	.018	.018	.344	.023
STIMULI PAIR (CODES)	D3HD-D2	D1HD-D3	D2HD-D3	D3HD-D3	D2HD-D1HD	D3HD-D1HD	D3HD-D2HD	
Z	-4.280[b]	-.638[c]	-.626[b]	-3.201[b]	-.725[b]	-3.929[b]	-3.557[b]	
ASYMP. SIG. (2-TAILED)	.000	.523	.531	.001	.468	.000	.000	

[b] Based on positive ranks

[c] Based on negative ranks

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Maximum decrease of horizontal distances between symbols with height differentiation applied (D1HD) did not cause significant differences in average solving times compared to D2 and D3 stimuli variants. Significant difference was noted when comparing with the D1 variant (average solving time longer by 01:58, Z = 2.366 $p<0.05$).

As expected, the D1 variant was the most problematic. A majority of study participants were unable to solve tasks 1 and 3 on this stimuli variant. Yet, we can observe how important the height differentiation of tactile symbols is, when we compare the total number of unsolved tasks 1 and 3 for variants without and with height differentiation applied: 83 and 3 respectively.

The above provides answers to the first and second research questions (RQ1, RQ2). Based on the results presented, we have confirmed the hypothesis that it is possible to reduce the suggested minimum horizontal distances even threefold (from 3 to 1 mm), when applying height differentiation of tactile symbols.

Participants' feedback

During the study we have also gathered participants' feedback in a form of questionnaires. We wanted to learn their opinions about the quality of the stimuli prepared, their cartographic soundness and if the tactile symbols selected were appropriate. We were especially interested in how the material used for 3D printed maps performed in terms of haptic comfort and also the general level of understanding of the maps presented (Fig 9).

Participants highly appreciated the ease of understanding the maps (26 individuals answered yes or definitely yes) and the comfort of using them (28 individuals answered yes or

Table 9. Task 3 –ranks.

STIMULI PAIR (CODES)		N	MEAN RANK	SUM OF RANKS
D2-D1	Negative Ranks	7[a]	4.00	28.00
	Positive Ranks	0[b]	.00	.00
	Ties	0[c]		
	Total	7		
D3-D1	Negative Ranks	6[d]	4.17	25.00
	Positive Ranks	1[e]	3.00	3.00
	Ties	0[f]		
	Total	7		
D1HD-D1	Negative Ranks	7[g]	4.00	28.00
	Positive Ranks	0[h]	.00	.00
	Ties	0[i]		
	Total	7		

(*Continued*)

Table 9. (Continued)

STIMULI PAIR (CODES)		N	MEAN RANK	SUM OF RANKS
D2HD-D1	Negative Ranks	7[j]	4.00	28.00
	Positive Ranks	0[k]	.00	.00
	Ties	0[l]		
	Total	7		
D3HD-D1	Negative Ranks	7[m]	4.00	28.00
	Positive Ranks	0[n]	.00	.00
	Ties	0[o]		
	Total	7		
D3-D2	Negative Ranks	20[p]	14.35	287.00
	Positive Ranks	7[q]	13.00	91.00
	Ties	3[r]		
	Total	30		
D1HD-D2	Negative Ranks	18[s]	15.47	278.50
	Positive Ranks	12[t]	15.54	186.50
	Ties	0[u]		
	Total	30		
D2HD-D2	Negative Ranks	21[v]	15.36	322.50
	Positive Ranks	8[w]	14.06	112.50
	Ties	0[x]		
	Total	29		
D3HD-D2	Negative Ranks	28[y]	15.73	440.50
	Positive Ranks	2[z]	12.25	24.50
	Ties	0[aa]		
	Total	30		
D1HD-D3	Negative Ranks	14[ab]	13.43	188.00
	Positive Ranks	15[ac]	16.47	247.00
	Ties	1[ad]		
	Total	30		
D2HD-D3	Negative Ranks	18[ae]	12.81	230.50
	Positive Ranks	10[af]	17.55	175.50
	Ties	1[ag]		
	Total	29		
D3HD-D3	Negative Ranks	22[ah]	17.64	388.00
	Positive Ranks	8[ai]	9.63	77.00
	Ties	0[aj]		
	Total	30		
D2HD-D1HD	Negative Ranks	17[ak]	14.76	251.00
	Positive Ranks	12[al]	15.33	184.00
	Ties	0[am]		
	Total	29		
D3HD-D1HD	Negative Ranks	24[an]	14.69	352.50
	Positive Ranks	3[ao]	8.50	25.50
	Ties	3[ap]		
	Total	30		
D3HD-D2HD	Negative Ranks	23[aq]	13.72	315.50
	Positive Ranks	3[ar]	11.83	35.50

(*Continued*)

Table 9. (Continued)

STIMULI PAIR (CODES)		N	MEAN RANK	SUM OF RANKS
	Ties	3[as]		
	Total	29		

a. D2 < D1
b. D2 > D1
c. D2 = D1
d. D3 < D1
e. D3 > D1
f. D3 = D1
g. D1HD < D1
h. D1HD > D1
i. D1HD = D1
j. D2HD < D1
k. D2HD > D1
l. D2HD = D1
m. D3HD < D1
n. D3HD > D1
o. D3HD = D1
p. D3 < D2
q. D3 > D2
r. D3 = D2
s. D1HD < D2
t. D1HD > D2
u. D1HD = D2
v. D2HD < D2
w. D2HD > D2
x. D2HD = D2
y. D3HD < D2
z. D3HD > D2
aa. D3HD = D2
ab. D1HD < D3
ac. D1HD > D3
ad. D1HD = D3
ae. D2HD < D3
af. D2HD > D3
ag. D2HD = D3
ah. D3HD < D3
ai. D3HD > D3
aj. D3HD = D3
ak. D2HD < D1HD
al. D2HD > D1HD
am. D2HD = D1HD
an. D3HD < D1HD
ao. D3HD > D1HD
ap. D3HD = D1HD
aq. D3HD < D2HD
ar. D3HD > D2HD
as. D3HD = D2HD

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Table 10. Geometric measures of line and area symbols on tactile stimuli.

Stimuli variants		D3/D3HD	D2/D2HD	D1/D1HD
Line symbols	Total length [mm]	1935.9	1981.3	2008.9
	Increase	0.00%	2.34%	3.77%
Area symbols	Total length [mm]	1933.0	2021.1	2128.0
	Increase	0.00%	4.56%	10.1%
Sum of lengths [mm]		3868.9	4002.4	4136.9
Average increase		0.00%	3.45%	6.93%

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definitely yes). This assessments did not depend on the level of experience with tactile maps (understanding and level of experience: Kruskal-Wallis test $\chi 2(3) = 3.341$, $p = 0.188$; comfort and level of experience: Kruskal-Wallis test $\chi 2(3) = 3.245$, $p = 0.197$), which suggests that the assessment is related to the map properties.

Study participants made a number of suggestions on how to modify tactile stimuli for better distinguishability and legibility. All of the feedback presented in this section has been mentioned by at least 3 participants of the study.

We asked the participants whether some symbols were too similar or too close to each other that made them hard to perceive. In general, many participants were confusing circle with triangle and square. One of the suggestions that could prevent misidentification was to use both types of point symbols within one map: full-infill and outlines only. This would result in different roughness when touching a symbol. Besides, it turns out that rounding tactile symbols can cause confusion when it comes to distinguishing similar shapes, e.g. square from circle. We have applied rounding to raise the tactile comfort. Thus, it is a matter of trade-off between legibility and comfort.

Another interesting suggestion was to use isosceles triangles instead of equilateral ones to differ them from circles even more. More generally, the point symbols should be bigger according to the participants.

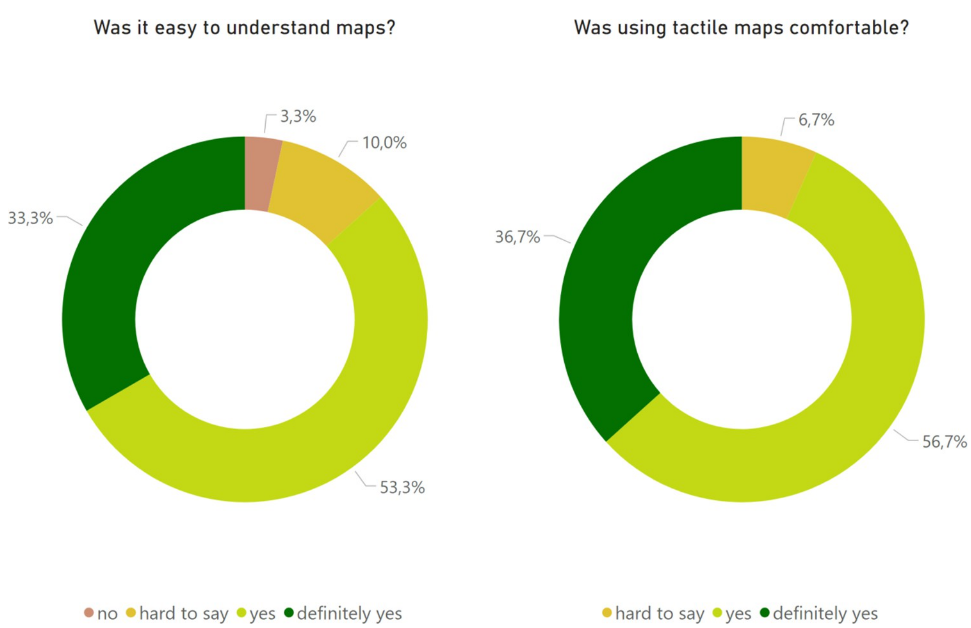

Fig 9. Results of the post-study questionnaire.

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Another very common comment was that sometimes it was hard to find circles (task 1) or paths (task 3) that were "hidden" within textures (area symbols). Participants who realized that in some stimuli variants height differentiation of tactile symbols was applied, pointed out the importance of this design feature. Some participants, even without noticing this modification, said that it would be very helpful to put point symbols above the textures to identify them more easily.

Some participants indicated too similar pairs of textures (e.g. zig-zag and line patterns) but the comments were very diverse and we were not able to determine, which pattern was the most confusing one.

During the study, we have also asked participants about their personal opinions and comments about the study and how to improve the future tactile maps. We have selected some of the most popular comments:

- Many of the participants pointed out that the symbols used on the stimuli have different meanings on maps that they know. For example, one of the textures used on the stimuli is commonly used for depicting water bodies on Polish tactile maps. Others expressed the need for tactile symbols standardization more explicitly.
- Even though we have applied height differentiation on selected stimuli variants, some participants said that it would be a good idea to differentiate them even more.
- There was no consistency in terms of proper minimum distance between symbols on tactile maps. Based on the comments gathered and our observations during the study, the higher distances sometimes caused confusion when tracking a path (task 3)–"is it still the same path or a new one?", whereas too low distances caused the participants to select wrong paths at the crossroads. Perhaps, a 2 mm distance would be the most optimal choice?

Information value gain

Using the 3D modelling software, we have calculated the lengths of particular tactile symbol types on each of the stimuli variants' vector drawings. In case of line symbols, the lengths of axes were evaluated, whereas for area symbols, we have measured their outline lengths (Fig 10). Point symbols were not taken into consideration in this study as their number did not vary across stimuli variants.

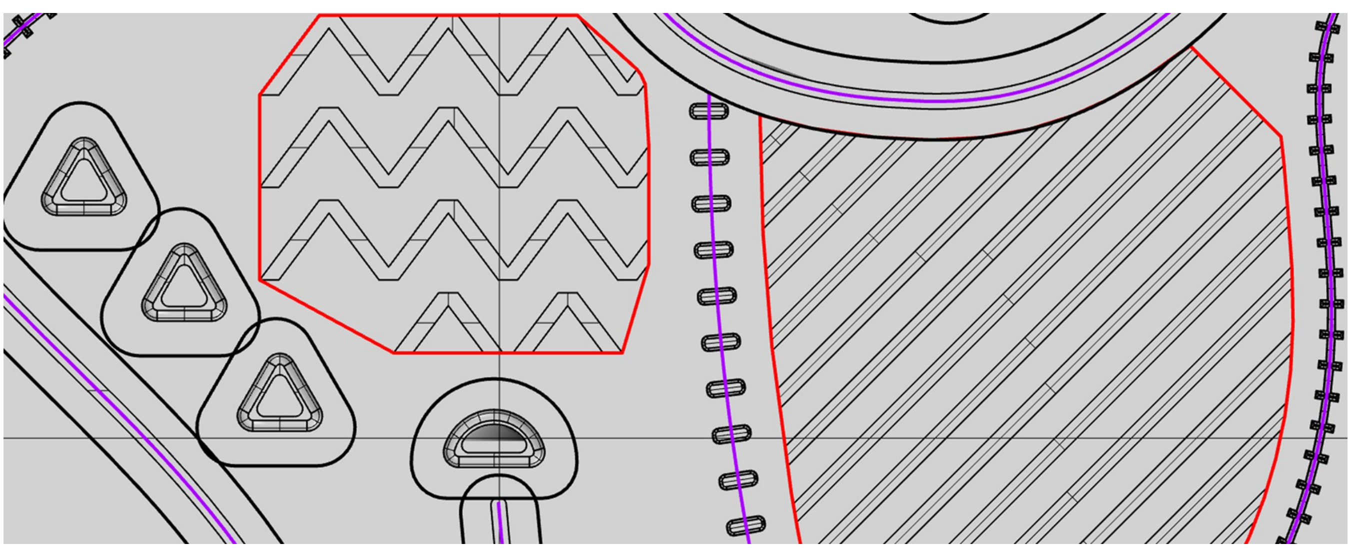

Fig 10. Vectors used for calculation of information value. Lines' axes are marked in purple, area symbols' outlines in red.

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The measures taken have been used for calculation of potential information value gain thanks to the reduction of minimum horizontal distances between symbols (Table 10).

The potential increase of information value reaches over 10% in terms of area symbols for minimum horizontal distance reduction from 3 to 1 mm. If we average the two evaluated symbol categories, we will get approximately a 3.5% and 6.9% increase when reducing the minimum distances to 2 and 1 mm respectively. This is a significant increase if we consider the costs of tactile map production and how complex the process of tactile map generalization is. This analysis provides an answer to the third research question (RQ3).

The real information gain could be even higher as the additional haptic variable of height can introduce new spatial information, e.g. the higher the symbol representing a city, the more population this city has, as it was previously described by Wabiński et al. [11].

Discussion

The results of our study further extend the conclusions described by Nolan and Morris [19]. In their study of seeking optimum tactile symbol design for maximum legibility, one of the tasks was to follow the path denoted by a dotted line on photo engraved tactile maps. Their results proved the application of height differences to be a significant factor in time required to follow the path, whereas minimum horizontal distances between particular symbols were not significant. Thus, we can conclude that the findings are not dependent on the production method used.

Based on the participants' feedback we can assume that the issues raised in previous studies regarding difficulties in access to high quality tactile maps [37] still exist. PVI have no experience in working with tactile maps as they are often not even aware of the existence of such materials in public spaces. For this reason not only the issues with production of new tactile maps should be emphasized but also the ways to inform about the existing ones.

Until today, there was not much research comparing various tactile maps production methods. Previous studies did not agree on the best production approaches [38, 39]. But using 3D printing for tactile map production looks promising. 3D printed maps tend to be rough in touch but as it was stated in the past [19, 40, 41] as well as in our qualitative analysis, PVI prefer this kind of tactile stimuli.

Our long-term goal is to convince users and producers of tactile maps that 3D printing can be successfully used for generation of cheap, legible, and unique map sheets. According to Leonard & Newman [42], researchers should look for standardized procedures that can be applied locally and at relatively low cost and without expensive equipment in terms of tactile aids production. This was an issue back then but even now, more than 50 years later, many PVI lack tactile aids. This is also true for developed countries [25, 43].

In order to quickly generate cheap tactile maps, a repeatable process of their development is necessary. This requires standardization, including strictly defined parameters of symbol design and map editing. They make it possible to automate and speed up the entire process of map generation. Previous studies have not developed unequivocal parameters, but rather recommendations. These recommendations usually do not inform, what printing technique should be used along with them. Therefore, they are not enough to standardize the process of tactile maps development.

3D printing makes it possible to use an additional tactile variable–height, that is currently rarely used. Using this additional variable, it was possible to reduce the distances between the symbols in our study. In this context, the existing recommendations regarding the designed symbols and map redaction should be redefined. The parameters for 3D printing technique were defined in our study and could be reused in the future. They can be the starting point for standardization and automation of tactile maps development process.

Increasing the readability of maps using height differentiation is not dependent on personal factors–no significant differences were found in average solving times of both congenitally/early and adventitiously blind or those with different levels of Braille reading skills and experience with tactile maps.

Using 3D printing as a method for production opens many possibilities in terms of fast and accurate development of not only tactile maps, but educational tactile materials in general. As it turned out, the vast majority of our study participants (over 90%) indicated their satisfaction when using 3D printed tactile stimuli. Most of them found working with 3D printed tactile maps pleasant and not tiring (even in the face of relatively long study sessions). At the same time, many of them were very intrigued by the possibility of printing similar maps on demand in a fast and cheap way using such printing method. Educators across the world should consider implementing 3D printing in their labs as a method for tactile materials preparation, especially in the face of the rapid development of this technology that leads to significant cost reduction of printing equipment and materials.

Conclusions

This paper's aim was to systematically assess our hypothesis that using height differentiation of symbols on tactile maps facilitates their reading and allows reduction of minimum distances between particular symbols. Our results confirmed this hypothesis.

Thanks to the qualitative analysis conducted during the study sessions, we have learned a lot about expectations of PVI in terms of tactile maps design. We consider this a significant step towards more efficient and cheaper tactile map production and possibly, the automation of this process, along with standardization of tactile symbols on maps.

In this study we wanted primarily to compare stimuli variants: D3 and D1HD as they represented our hypothesis in the clearest manner. D3 is the variant prepared according to the existing good practices. We wanted to prove that applying height differentiation may allow reduction of the minimum distances between tactile symbols (D1HD). When looking at the quantitative results of our study, we can see that average solving times for the D1HD variant were either definitely lower (task 1) or comparable (tasks 2 and 3). Although the differences in solving times between these two variants were not statistically significant, D1HD was more efficient when it came to identifying point and area symbols as well as–to a lower extent–line symbols. Thus, we can conclude that it is possible to reduce the suggested minimum horizontal distances between symbols on tactile maps by applying height differentiation and at the same time, gain additional space that may be used to put more relevant information or simply increase map's legibility.

We believe that our study has once again shown the importance of tactile maps design standardization. Some study participants were disoriented by some of the symbols used, even though they were carefully selected.

In future research we would like to further evaluate possibilities of tactile maps information value improvement by differentiating heights of tactile symbols within one geometry type. Besides, we want to focus on the issue of tactile symbols standardization. The first steps have been taken and we would like to involve the practitioners across the globe to share their experiences in this area.

Besides, we plan to apply the knowledge gained during this study to form parameters that will control the process of automatic or semi-automatic tactile map generalization out of digital spatial data publicly available thanks to initiatives, such as the INSPIRE directive [44].

Besides, we would like to analyse map reading techniques and participants' behaviour based on the video material recorded during the study sessions to learn about the most efficient ways of tactile maps scanning.

This study has left us with a number of valuable suggestions on how to improve tactile maps that should be considered in the processes of tactile map development. Besides, they ought to form a part of potential official tactile maps design guidelines.

However, the needs of every PVI differ. Particular symbols were confused by some participants, whereas others had no troubles in distinguishing them. Some participants preferred the legend to be separate from the map, whereas others would like it to be an integral part of the map. All that allows us to confirm past conclusions that preparing tactile map design standards suitable for all PVI is a real challenge.

Supporting information

S1 File. Research protocol. Formal description of the testing phase.
(DOCX)

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SURVEY PAPER

Guidelines for Standardizing the Design of Tactile Maps: A Review of Research and Best Practice

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ABSTRACT
Accessibility to tactile maps is limited due to their expensive and time-consuming development. Acceleration of their production requires standardized design guidelines that consider symbol design and production methods. In this paper, based on a review of research and best practice, we summarize knowledge on how to design tactile maps properly and provide a selection of highly legible, recommended symbols for the compilation of tactile maps. We also examine generalization constraints and other design parameters that are necessary for the standardization of tactile mapping. Finally, we explore differences in tactile map design depending upon the selected production method. Over the years, many useful guidelines have been developed although they remain unknown to the wider audience. There is still a long way to go in creating a global standard for the design of tactile maps.

KEYWORDS
Tactile maps; design principles; standardization; symbology; production methods; guidelines

Introduction

We are living in the information era and many people benefit from the abundance of freely available spatial data. New technologies facilitate the production of tactile maps (e.g., Götzelmann and Pavkovic, 2014; Barvir *et al.*, 2021), but we still lack straightforward methodologies on how to compile these data into a legible form for people with visual impairments (PVI) in a controlled and repeatable manner, while keeping the processes of production relatively fast and cheap. In order to do so, as in the case of traditional maps, we should aim to use the procedures, devices and software that allow repetitiveness of the map generation process and minimize unnecessary subjectivity. Standardization is an important step in achieving these goals.

The standardization of tactile mapping requires the unification of the principles of their preparation in such a way that, regardless of the designer, the quality of the equivalent maps (covering the same topic and area), prepared by other creators, should remain at a similar level. It is thus necessary to develop standardized design rules, optimal criteria, and measurable parameters for the tactile map production scheme that would reduce the level of subjectivity of the final result. For example, knowing the minimum recommended height differences between two components on a map would help mapmakers in their design choices. Moreover, such an approach increases reproducibility of tactile maps, minimizes errors, speeds up their development, and reduces costs related with their production. This, in turn, increases the accessibility to tactile materials for PVI.

The production of tactile maps is usually less formal than their traditional counterparts. The existing standards alone (e.g., BANA and the CBA, 2010; ISO, 2016) do not provide full methodologies on how to modify spatial data to produce tactile maps. Thankfully, combining findings of the existing literature and research in this field, together with the best practices developed by the practitioners designing such maps might, at least partially if not completely, bring us closer to the full methodology of tactile map production for everyone - not just expert computer users or professional cartographers. This would be a milestone in the standardization and, consequently, the, acceleration of their development. Therefore, the main aim of this paper is to review guidelines for the design of tactile maps and extract rules and parameters that could be defined to standardize (at least partially) the process of their production.

This manuscript is structured as follows. First, we summarize the current state of the art of tactile map production and standardization. Second, we present the methodology of our research along with the scope of our analysis, and seek answers to our research questions:

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- What are the recommendations for tactile symbol design?
- What are the recommended tactile symbols?
- What generalization parameters (and their values) can be defined for tactile mapping?

Third, we describe the results of the analysis with emphasis on recommendations resulting from the literature and best practices. Finally, we discuss our findings and propose future work in the area of tactile mapping standardization.

State of the art

Tactile mapping

The main difficulty that distinguishes traditional from tactile mapping is the need to transform visual information into a form that can be perceived by other senses (mainly touch). This, in turn, requires a certain level of map content simplification and abstraction in comparison with traditional maps, because a person without visual impairments is usually able to distinguish points and lines that are 0.15 mm apart (Yanoff and Duker, 2009), whereas using the sense of touch, this value increases to 2.4 mm (Klatzky and Lederman, 2003). This implies the need for a higher level of generalization of spatial data for the preparation of a legible tactile map. Generalization itself is a complex and difficult research topic in cartography, but should attract even more attention in the field of tactile cartography due to the perceptual characteristics of touch (Touya *et al.*, 2019).

The difficulty in compiling tactile maps from traditional maps is not only about simplifying their content. Even for general navigation, some features that are usually not put on traditional maps need to be added, e.g., exact locations of traffic lights at pedestrian crossings. Little attention has also been paid to thematic tactile mapping (Perkins, 2002; Wabiński and Mościcka, 2019). This results in a lack of educational materials that would allow pupils at schools for the visually impaired to fulfil curricula of subjects such as geography or history. The source of this problem is that, currently, practically every tactile map should be approached individually.

Due to the high complexity of the above problems, the process of creating tactile maps is difficult and requires the involvement of a number of specialists (Więckowska *et al.*, 2012; Mukhiddinov and Kim, 2021). It causes the production of tactile maps (and tactile graphics in general) to be both time-consuming and expensive (Gual *et al.*, 2015; Brittell *et al.*, 2018; Wabiński *et al.*, 2020). The cost aspect can be even considered prohibitive (Stangl *et al.*, 2019). Therefore, issues associated with tactile cartography tended to be marginalized and were largely unappreciated by the broader cartographic community.

The situation has recently changed due to the development of computer techniques and increasing awareness of the needs of people with disabilities. The popularity of concepts of inclusiveness and universal design has grown significantly. This can be observed in the amount of research being published that is related to the needs of PVI. It includes research related to tactile maps, i.e., maps for PVI with convex elements dedicated to reading by touch that also contain highly contrasting visual elements. The last decade has brought a significant increase in working solutions for tactile map production that either adapt existing spatial data (e.g., Watanabe *et al.*, 2014; Hänßgen, 2015; Červenka *et al.*, 2016) or convert hand-drawn maps (e.g., Takagi and Chen, 2014; Pandey *et al.*, 2020). Research in this area can be summarized by a number of literature reviews regarding tactile graphics from just the last three years: on touch-based accessible graphics (Butler *et al.*, 2021), tactile cartography in the digital age (Cole, 2021), automatic creation of tactile graphics (Mukhiddinov and Kim, 2021), as well as automatic tactile maps generation (Wabiński and Mościcka, 2019). The aesthetics of tactile mapping has also been discussed (Kent, 2019).

Unfortunately, researchers often focus on the possibilities of modern techniques without a full understanding of all the issues related to tactile mapping. As a consequence, many emerging solutions aimed at helping PVI are designed in research laboratories and do not prove to be useful in everyday life. Incorrect approaches in evaluations of technology for PVI are raised by Brulé *et al.* (2020). Their research concludes that it is of great importance to take a participatory and inclusive approach by inviting PVI to the research activities and get their feedback on whatever solutions are designed.

Although many of the aforementioned problems in tactile mapping are well known, methodological and technical solutions are still missing. They are particularly essential for the most subjective tasks in the development of tactile maps: cartographic editing and appropriate generalization (e.g., Červenka *et al.*, 2016; Taylor *et al.*, 2016) that require manual editing by experienced cartographers of tactile maps to obtain a legible product. This problem is tackled by Eriksson *et al.* (2003: 47), who noted that 'copying of a visual map without revision into a tactile form of the same size would result in a map that is difficult or impossible to read because of its being too cluttered'. Thus, a straightforward transcription (as mentioned by Cole, 2021) of a visual map is not an appropriate solution.

These difficulties cause a significant discrepancy in the level of development between traditional and tactile mapping. Traditional mapping is supported by a number of solutions that largely speed up and simplify the mapping process. This includes the standardization of mapping rules as well as dedicated software for implementing them. To the best of our knowledge, there are still no solutions capable of developing tactile maps systematically that are based on the specific demands of tactile map reading.

Standardization attempts

The first attempts to standardize tactile mapping were attempted almost 50 years ago. One of the best-known examples is *The Nottingham Kit* that was applied widely to the tactile mapping of urban areas (James, 1975), and was later enhanced to form a European-wide standard: *Euro-Town-Kit* (Laufenberg, 1988). This was, however, never meant to be an universal standard for all types of maps.

Fleming (1990) anticipated that tactual mapping research will continue to focus on the development of a standard set of symbols, and the refinement of production and reproduction techniques. The author also stated that several nations follow certain design guidelines but standardization has not been achieved at the international level. Although many new production methods have appeared since 1990, we have still not come to an agreement upon a standardized set of symbols. The obstacles in the way of standardization are numerous differences of perception among individuals with visual impairments and differences between various production methods of tactile maps. Besides, the intended purpose of a map influences its design. All of the above contributes to the complexity of the standardization process.

Many countries have proposed their own guidelines, e.g., Australia (The NSW Tactual and Bold Print Mapping Committee, 2006), Mexico (Instituto Nacional de Estadisticas y Geografia, 2017), Poland (Olczyk, 2014), Sweden (Eriksson *et al.*, 2003), and the United States and Canada (BANA and the CBA, 2010). International standards also exist (ISO, 2013, 2016, 2019), but take a very technical approach. Unfortunately, although characterized by invaluable expertise and insight, these guidelines are neither globally recognized nor universally applicable within the domain of tactile map generation. This is due to many issues, such as the dispersion of these works, the absence of officially published materials (they exist mainly in the form of working papers), their elaboration in different languages, and the lack of cooperation between researchers and institutions working on these guidelines that have been raised in other research (Wabiński and Mościcka, 2019; Mukhiddinov and Kim, 2021).

Over the years, institutions and researchers attempted to create universal solutions in the field of tactile map standardization. Cole (2021: 835) concludes that even though 'the standardization of tactile mapping practices has been on the to-do lists of many researchers for decades, […] tactile *mapping* standards have never quite made it past the proposal stage'. One such example is the *Tactile Graphics Project* launched in 2000 by the International Council on English Braille that aimed at creating international production guidelines, but now seems discontinued (ICEB, 2002). We were unable to find any similar projects being implemented in subsequent literature.

Methodology

Our research is based on the assumption that a comprehensive understanding of guidelines for tactile mapping requires both scientific and practical knowledge. Scientific knowledge is mainly derived from published research and often remains unimplemented in practice, but reveals new rules or dependencies. Such knowledge is usually well disseminated in the recognized international journals. Practical knowledge is acquired mainly from practitioners' best practices. This knowledge, at least in the field of tactile mapping, is usually applied only on the local level and is not published globally in English. Such knowledge is invaluable due to its practical applications. However, in our opinion, only the combination of theoretical knowledge and practical applications provides a comprehensive recognition of the topic, especially one as specialized as tactile mapping.

Scope of analysis

This study applies a critical analysis of sources and involves two main stages. First, the problem of establishing guidelines for tactile mapping was divided into issues covering all important aspects involved in the process of tactile map design: editing and reproducing. Then each of these issues was examined separately within both types of the analysed sources: research and best practice. Regarding the process of tactile map development, the following issues were analysed:

(1) **Recommendations for tactile symbol design,** i.e., the requirements to be met by symbols so that they reflect reality in the best possible way and are understandable for PVI, e.g., by using the simplest shapes possible that still resemble the features mapped. These recommendations are related to the geometrical characteristics of point, line and area symbols, as well as inscriptions. Every symbol type is considered separately due to its individual characteristics. Many rules related to symbol design are described only in locally applied best practices and guidelines that are derived from the expertise of tactile map cartographers and other specialists involved in their development (Więckowska *et al.*, 2012). These documents usually take the form of a set of best practices rather than concrete and explicit guidelines.
(2) **Recommended tactile symbols**, which include symbols that were found to be easily distinguishable in the former studies, such as those recommended for the compilation of tactile maps, e.g., square and asterisk point symbols. This issue is strongly related to the previous one. Some of the symbols, designed according to the above recommendations, have already been tested for readability among PVI. Some sources recommend sets of symbols along with, if applicable, their meaning and dedicated production method. Although not all the sources provide such detailed information, many symbols can be considered as a source of inspiration for individual experiments and for further modifications.
(3) **General rules for tactile maps editing,** which are related to tactile map composition as a whole. These include mathematical foundations, e.g., scale, legend, and sheet format; but also those more specific to tactile maps, such as durability and portability, e.g., a convex triangle in the top right-hand corner of a map serving as an orientation mark. This issue covers both the general rules of implementation and the numerical parameters connected with them. As many steps in tactile mapping remain very subjective and there are no guidelines on how to proceed in given situations, we reviewed wider cartographic studies in search of useful methodologies on how to design maps appropriately, including guidelines that can be directly implemented in tactile cartography. As in traditional cartography, when designing tactile maps, a number of questions should be answered prior to their creation: who will use the map and in what way? Where and when will it be used? The answers determine the topic of the map, its content and format (Gardiner and Perkins, 2002). We assumed that applying well-tested rules for traditional cartography may be more effective than searching for completely new solutions that are specifically tailored for tactile cartography.
(4) **Numerical parameters governing the map content development.** This involves defining the measures that should be considered in both the creation of tactile symbols and their arrangement on the map, e.g., the minimum distances to be maintained between symbols on tactile maps. The issue is related to the perception abilities of the readers that determine measurable parameters such as the size of symbols and the distances between them. Such parametrization is essential to ensure repeatability and also the standardization of map production.
(5) **The characteristics of different production methods** that hinder the standardization of tactile maps. They require different approaches of map preparation and influence its application. Some techniques produce softer and less durable maps, that are also foldable results (e.g., swell paper), some are widely-known to PVI but require specialist hardware (e.g., thermoforming), whereas others allow the production of any geometry but still face technological limitations (e.g., 3D printing). Each of these characteristics has to be considered during cartographic editing, as even when following the same methodology, the final result might differ due to the production method used.

Analysed sources

Research

The primary studies analysed in this review come mainly from our literature databases gathered during previous research and stored in our reference management system. Many of the older studies were identified from the references cited in the aforementioned sources. In our previous systematic literature review on automatic tactile map generation, we identified almost 600 primary studies, out of which many were eligible for this research (Wabiński and Mościcka, 2019).

We also conducted a non-systematic search of selected databases, e.g., Scopus and Web of Science, using keywords with their alternative spellings and synonyms. The primary set of keywords included: 'tactile maps guidelines', 'tactile symbols', 'tactile maps standardization', 'automatic map generalization', and 'tactile symbols recommendations'.

Best practice

Local best practice, due to the practical approach and expertise of its authors, can significantly contribute to the standardization of tactile mapping. One of the research questions suggested by Commission members of the International Cartographic Association (ICA) is 'How to encourage more cartographic experts to share their knowledge and teach beginners?' (Griffin *et al.*, 2017: 3). We assume that performing questionnaires about tactile mapping guidelines in different countries is a form of such encouragement and will enable us to supplement our scientific knowledge about tactile mapping guidelines with the knowledge of practitioners. Hence, we decided to conduct such a questionnaire prior to this study. The main goal was to learn what best practices are being applied around the world for the process of designing tactile maps. Most of the subject literature, whether in scientific journals or on web pages, is published in English. By conducting this questionnaire, we tried to reach practitioners from different parts of the world and to obtain some unrecognized 'grey literature' that has been published in other languages.

The online questionnaire contains 20 questions concerning, inter alia: printing methods, existence of guidelines or best practice documentation, minimum dimensions of symbols and distances between them as well as the height differentiation of symbols. The questionnaire was disseminated using a mailing list of the ICA Commission on Maps and Graphics for the Blind and Partially Sighted. We obtained eight responses from tactile map designers representing seven different countries (Brazil, Canada, Iraq, Mexico, Poland, UK and US). No single guidelines document was mentioned more than once, which means that every response is based on different guidelines, even within one country. One of the respondents indicated that no particular guidelines are followed in his/her country as tactile maps are not yet widely produced. On one hand, this confirms our concerns about the lack of standardization and cooperation between practitioners from different countries, but at the same time, it provides us with useful material for analysis.

Many of the questions referred to particular design rules, but interestingly, there was usually no agreement among respondents. In questions about the minimum size of symbols of different geometry on tactile maps, only some respondents provided specific values (e.g., 6 mm). Others referenced particular guidelines, or did not provide explicit values but commented on the dependency of this value upon many factors, such as the production method used, target user group or map topic. The same disagreement was true for the remaining questions concerning specific dimensions used on maps, as well as the number of unique textures used on a single tactile map – the answers ranged from 2 to 20 possible textures, although this last value might come from a misunderstanding of the question asked.

We can assume that those respondents who provided explicit values are those who design fixed types of tactile maps for a specified target group and use selected production methods, whereas those who produce a wider variety of tactile maps have to amend these parameters according to the intended purpose of a map. In turn, general agreement can be reported in terms of used map sheet formats. Every respondent answered the related question providing specific formats or their dimensions. It turns out that the vast majority of the respondents use formats similar to A4 or A3 standards. Based on the reported positive impact of height differentiation of tactile symbols on tactile maps legibility (e.g., Holloway *et al.*, 2018; Wabiński *et al.*, 2022), we were surprised by a considerably low number of respondents that apply this feature on their tactile maps (only 25% of the respondents). We also asked about the production methods used for tactile map production (Figure 1). Thermoforming, swell paper and hand-crafting remain the most popular production methods, regardless of the recent developments. We analyse the detailed results of the questionnaire in the following chapters in relation to our research questions, together with the analysis of the scientific literature in this area.

Results

What are the recommendations for tactile symbols design?

The starting point in the design of tactile symbols is the same as in traditional cartography – it is important to maintain the real-world object's characteristics (e.g., railroads symbolized as two parallel lines with transverse lines) and to keep them as simple as possible because simplicity is considered the second most important principle after legibility in tactile map design (Nolan and Morris, 1971). More complex symbols, such as stylized pictorial symbols, are hard to comprehend for individuals with adventitious blindness and partial sight (Wiedel and Groves, 1969), although more recent studies show that some aspects of perspective are understood by PVI (Kennedy, 2006).

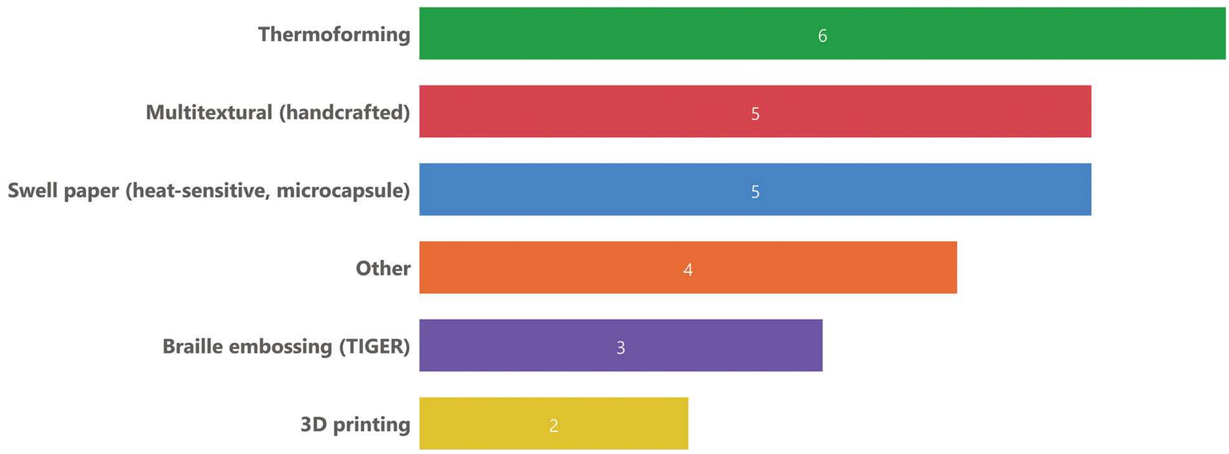

Figure 1. Production methods used by questionnaire respondents. Source: authors.

In general, the symbols on tactile maps should be differentiated along as many tactual dimensions (variables) as possible. Because different variables are used for different types of symbols (points, lines, areas and inscriptions), the recommendations for the design of tactile symbols were analysed separately for each of these groups.

Point symbols

Following the previous rule that symbols should be as simple as possible, simple geometrical shapes, such as circles, triangles, rectangles or squares should be used as point symbols (Bris, 2001; Polak and Olczyk, 2010; ISO, 2019). Other resources suggest supplementing this set by one of the following: cross, plus symbol and asterisk (The NSW Tactual and Bold Print Mapping Committee, 2006). Although more complicated 3D point symbols were found to be legible by Holloway *et al.* (2019), they require considerable gaps between symbols (minimum 1 cm). Apart from overall shape, Nolan and Morris (1971), list four features that impact the discriminability of point symbols: form, size, solid-outline and continuous-interrupted (Figure 2).

According to Polak and Olczyk (2010), the easiest point symbols to perceive are unfilled symbols that use only an outline. Moreover, small point symbols of the same shape (e.g., a circle) should not appear on a single map in two versions, e.g., as filled symbols and outline symbols (Eriksson *et al.*, 2003). According to French guidelines (Bris, 2001), standalone point symbols should not be the same as those used to form area symbols (textured elements) on the same map, even if they differ in size.

Line symbols

Nolan and Morris (1971) identify four features that impact the discriminability of a line symbol: whether a line is continuous-interrupted, smooth-ragged, single-double, or thick-thin. Generally, using single lines is usually recommended because they result in faster exploration times and better memory representations than double lines (Bentzen and Peck, 1979; Easton and Bentzen, 1980). Double lines require more space and slow down the rate of extracting information (Easton and Bentzen, 1980).

Regarding line continuity, Wiedel and Groves (1969) noted that broken or dotted lines are more easily recognized and followed tactually than smooth lines. But if dots are used for the line pattern, they should be either larger than 2 mm or smaller than 0.7 mm in diameter to avoid confusion with braille cells (The NSW Tactual and Bold Print Mapping Committee, 2006).

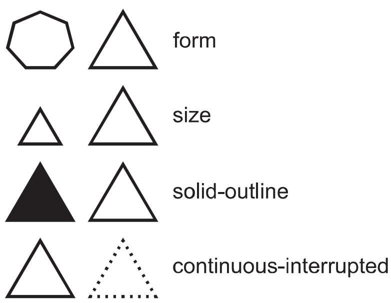

Figure 2. Different approaches for point symbol design. Source: authors.

To maximize legibility and avoid a potential injury or discomfort while reading tactile maps, cross-sections of line symbols should be in the shape of a semicircle or trapezoid. Squared shapes should be avoided (ISO, 2019). Nevertheless, tactile map designers should also pay attention in situations where line symbols topologically interact with other features. When a more important line intersects with a less important one, a small blank space at the intersection should be left (splitting the less important one) (James, 2009). This gap should be 2–3 mm (The NSW Tactual and Bold Print Mapping Committee, 2006). In general, single lines should not cross double lines (Amendola, 1976).

In the case of lines embedded in areal symbols, it is necessary to use at least two differing attributes between their characteristics. For example, if a continuous line is within a texture composed of continuous lines – they can be differentiated by line width and line texture (Barth, 1983) or by putting symbols at different heights (Wabiński *et al.*, 2022).

Area symbols

According to The NSW Tactual and Bold Print Mapping Committee (2006), area symbols are characterized by three dimensions: style (geometry of texture elements), pitch (distance between pattern elements), and thickness (width of pattern elements). Nolan and Morris (1971) identified additional characteristics: whether patterns are regular or irregular (pattern), composed of continuous or broken elements (continuity), and their sharpness. The shape of the textural element composing the pattern was found to be of lower importance – two symbols with the same pattern, continuity and pitch that were simply rotated by 90° were often confused. Thus, rotation should be applied together with some other variables.

A common issue in the design of tactile maps is that the number of textures to be used on a single map is limited. In some cases, the edges of areas that we do not want to distinguish with a unique texture may be marked with an asymmetrical line; smooth on one side and made of rectangular or triangular elements on the other (Polak and Olczyk, 2010). Another way to differentiate area symbols is to use different heights in adjoining surfaces (ISO, 2016; Wabiński *et al.*, 2022).

Inscriptions and Lettering

Placing labels on tactile maps is a complicated task because they take up much space. They should therefore be placed only where necessary and be as short as possible. Abbreviations are a good way of labelling features where there is not enough space to put full names. All abbreviations should be listed in the legend. Single Braille cell abbreviations cannot appear on a map as they are meaningless to a reader – a minimum of two cells (three preferably) should be used (The NSW Tactual and Bold Print Mapping Committee, 2006). It is also desirable to use codes for groups of objects that facilitate memorization of such descriptions by readers (Edman, 1992; Olczyk, 2014). For example, the Braille letters ‘oat’ stand for Atlantic Ocean, where ‘o’ is the code for oceans and ‘at’ stands for Atlantic. Polish guidelines suggest that when a Braille inscription does not fit within a small area, it might be placed in the adjacent area near the border and preceded with the ampersand symbol (Więckowska *et al.*, 2012).

Braille labels should be placed horizontally with the only exception of street descriptions written along their course. Such labels cannot be expanded to mimic area symbols as in traditional cartography, where labels are used to present certain areas covered by the labelled features. However, text labels can be used for describing smaller area features instead of introducing area symbols (Edman, 1992; ISO, 2016).

Large raised characters could be used instead of Braille to depict common features, such as P for parking, but neither serif fonts nor script type fonts with decorations (e.g., italics) should be used (ISO, 2019). The label size should be at least 14–18 pt (Wiedel and Groves, 1969; Edman, 1992; Polak and Olczyk, 2010; ISO, 2013, 2016), although according to Brazilian guidelines (de Mello, 2018), the font used should be Arial of at least 26 pt size. The letter spacing should be set to ‘normal’ or ‘expanded’ (The NSW Tactual and Bold Print Mapping Committee, 2006).

It is even possible to design a legible tactile map without using Braille labels if every symbol is unique and discriminable from all others applied on the same map (Gardiner and Perkins, 2002). However, other guidelines suggest that inscriptions should be used for description of unique features: ‘symbols have to be learned (not a trivial task) whereas Braille can be read immediately’ (The NSW Tactual and Bold Print Mapping Committee, 2006: 17). Another possibility is to use unified symbols that provide audio feedback (e.g., Barvir *et al.*, 2021).

What are the recommended tactile symbols?

One of the earliest studies concerning the legibility of tactile symbols was carried out by Heath (1958). Their study compared different area symbols prepared using Virkotype printing (dusting the wet ink-print image with a fine

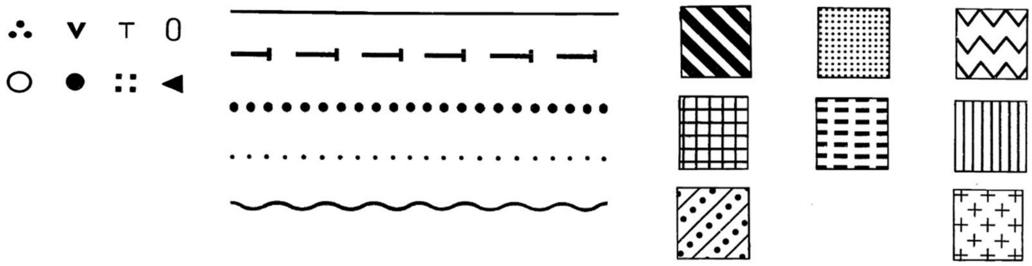

Figure 3. Highly distinguishable tactile symbols to be used with vacuum-forming. Based on Nolan and Morris (1971).

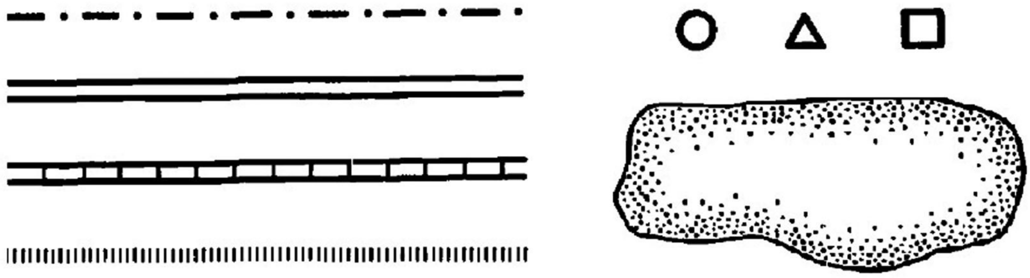

Figure 4. Tactile symbols that were found to be the most discriminable during the preliminary study (Wiedel and Groves, 1969).

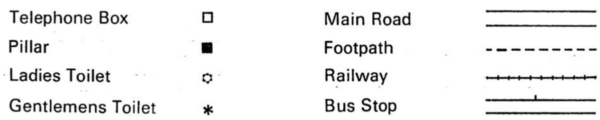

Figure 5. Selected symbols from the first described attempt to standardize tactile symbols. Based on James, (1975).

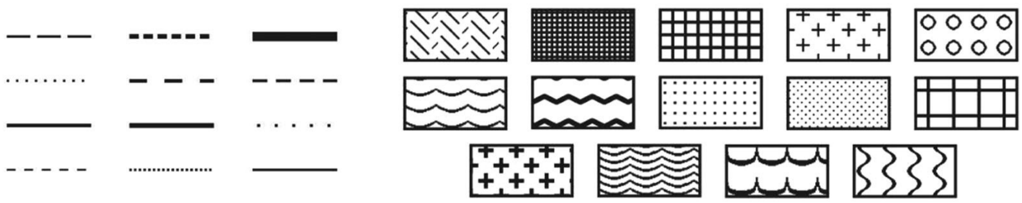

Figure 6. Highly distinguishable tactile symbols to be used with swell paper. Based on BANA and the CBA (2010).

resinous powder) in terms of their legibility. This was further extended by Nolan and Morris (1963) using a vacuum-formed technique. Similar studies were later carried out for point and line symbols and some authors also investigated the discriminability of point symbols used in Braille books (embossed paper) at the time. The results of these investigations are summed up in the final report by Nolan and Morris (1971) and some of the examples are presented in Figure 3.

Wiedel and Groves (1969) tested a number of different symbols for various map-based tasks as preliminary research. As a result, they managed to highlight the most distinguishable set of symbols that were later used during the project for various maps (Figure 4).

Having a set of symbols applicable within one study is an insufficient basis for standardizing tactile map production. Thus, a few years later, one of the first attempts to create a standardized set of tactile symbols was described by James (1975). This symbol set (Figure 5) was supposed to be used for orientation and mobility maps, either hand-crafted or vacuum-formed.

Similar investigations for the swell paper printing method were carried out by the Braille Authority of North America and the Canadian Braille Authority (2010). In their guidelines, one can find recommendations for the textures of area symbols, as well as propositions of distinctive line textures (Figure 6).

Some designs appear more frequently than others. For example, simple geometric forms such as squares and circles for point symbols, solid and dashed lines with various spacing and area symbols consisting of solid lines at different angles are the most common, regardless of the printing method considered. Thus, we can assume that such symbols are the most universal.

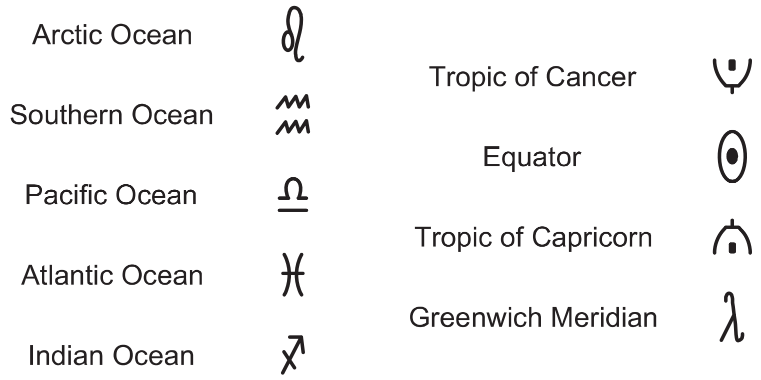

Figure 7. Proposition of standardized symbols for tactile world maps. Based on Regis and Nogueira (2013).

Whereas most of the studies focus on discriminability and aim at proposing legible symbols suitable for individual purposes, there are examples of research undertaken to propose standardized tactile symbol sets to depict unique real-world features, e.g., by Regis and Nogueira (2013). They proposed a set of symbols for the depiction of unique geographic features that are commonly presented on world maps, such as oceans or tropics (Figure 7), but, to the best of our knowledge, are not globally accepted. A table with all the extracted symbol designs along with more detailed descriptions may be found in the Appendix.

General rules for the creation of tactile maps

Best practice in tactile cartography not only considers the symbols themselves, but also their arrangement and the map's overall composition, which facilitates the preparation of a legible product for PVI. To consider a tactile map legible, a person with normal sight should be able to distinguish its main features (in bold print) from a distance of approximately 2–3 m (The NSW Tactual and Bold Print Mapping Committee, 2006). To achieve this, tactile maps cannot be cluttered. It is recommended to include no more than 10–15 distinct symbols (Rowell and Ungar, 2003), and no more than four (Więckowska *et al.*, 2012; Červenka *et al.*, 2013), or, according to Mexican guidelines, six, unique textures (area symbols) (Instituto Nacional de Estadisticas y Geografia, 2017) on a tactile map. Besides, according to the Polish guidelines, no additional graphic features, such as bar charts, or numerical values that describe map features, should be placed on tactile maps (Więckowska *et al.*, 2012). The same applies to inset maps, whose meaning might be too complex for PVI (Polak and Olczyk, 2010).

Tactile maps should also be small enough to relate their elements together within a maximum arm span of an average person (Bentzen, 1980; Edman, 1992). This goes in line with the need for tactile maps to be portable and usable in situ. However, some PVI in the studies cited indicate the need to study a map at home before putting it to practical use.

Keeping maps portable and legible requires a suitable level of generalization. As a result, all the mapped features might not fit onto one map sheet. In that case, map content could be split across several map sheets. Some features have to be repeated for easier comparison. The most common choice is to include hydrography on each of the maps in a series as a reference (Polak and Olczyk, 2010). Another approach is to split the same map into parts that would form a complete whole when joined. In this case, the cutting line should not interfere with any of the key features of the map. The map parts must be labelled, e.g., parts A and B (The NSW Tactual and Bold Print Mapping Committee, 2006).

Mathematical foundations of cartography are less important for the design of tactile maps and therefore some exceptions and unique design approaches can be applied. For example, according to Bentzen and Marston (2010), map scale does not necessarily have to be consistent in all parts of a map to be useful. Also, as suggested in the Polish guidelines, the tendency of using non-rounded scales (e.g., 1:985) on tactile maps is higher than in traditional cartography because cartographers of tactile maps have to exploit the free space on a sheet to the maximum extent (Więckowska *et al.*, 2012). However, whenever possible, consistent round scale denominators should be used, and also in map series (or atlases). Map scales should follow a logical sequence for easier comparison of dimensions (e.g., 1:300,000, 1:600,000) (Polak and Olczyk, 2010). Linear scales are useful for distance comparisons, but can be omitted on tactile maps in smaller scales (Wiedel and Groves, 1969).

If a map grid has to be presented on a tactile map, an appropriate cartographic projection should be used, so that the grid would be as simple as possible (straight lines or soft curves). Instead of full lines representing a map grid, one could use labelled ticks on the map border to symbolize meridians and parallels (Polak and Olczyk, 2010).

Although cartometry is of lower importance on tactile maps, they still require appropriate map miscellanea (e.g., title, authorship). These elements should be grouped together on a tactile map (typically in the top left-hand corner). The currency of information is particularly important for maps used for orientation and navigation. Thus, the date of production and the author's contact information should be mentioned on the map (Edman, 1992; ISO, 2016).

There is no agreement upon the placement of legends (keys). Some sources suggest placing them on the map sheet itself (The NSW Tactual and Bold Print Mapping Committee, 2006), whereas others suggest these should be placed on a separate sheet or on the last page of an atlas (Nogueira, 2009; Polak and Olczyk, 2010). When a legend is on a map sheet, it should be framed by thick lines that will distinguish it from the map's content (Wiedel and Groves, 1969). The map itself should also be framed using solid lines so that a reader would be aware of the neatline, or map limits (The NSW Tactual and Bold Print Mapping Committee, 2006). Also, all the symbols used on a tactile map sheet have to be included in a legend. Its elements should be placed in two vertical columns (symbols on the left and their explanations on the right) using exactly the same dimensions as those on the map sheet. First, tactile symbols should be listed, then Braille abbreviations with their explanations. If a 'you are here' symbol is used, it should appear first in the legend (Edman, 1992; ISO, 2016). As not all PVI can read Braille, labels in a legend should also be prepared in an audio form and/or as a large print underlay. This underlay should match the Braille character size and line spacing exactly (Gardiner and Perkins, 2002).

In Braille or audio legends, whenever a feature present on a map is mentioned, its abbreviation (if any) should also be mentioned (The NSW Tactual and Bold Print Mapping Committee, 2006). The audio description of a map should 'visit' every symbol on a given map and explain it. PVI prefer to listen to this information while reading a map and compare the audio with tactile information (Gardiner and Perkins, 2002). Whenever possible, hybrid maps for both PVI and their assistants or teachers should be prepared, e.g., in the form of transparent tactile overlays with raised elements put on appropriately designed visual underlays (Gardiner and Perkins, 2002).

Tactile maps, just like traditional maps, should withstand long-term use and remain unaffected by moisture or liquid. But their cartographers should also consider those characteristics that are usually omitted in traditional cartography. For example, tactile maps must be regularly cleaned. The material used should not cause allergic reactions, or get too hot or too cold due to the environmental conditions. Moreover, shiny surfaces should be avoided to prevent glaring effects – matt finish is preferred (ISO, 2016). Matt finishes also enhance the movement of a finger over tactile maps and facilitate the reading process (Rowell and Ungar, 2003). Detailed design rules and parameters for general map editing are presented in Table 1.

Unfortunately, although numerous rules and parameters can be extracted from existing studies, many gaps remain, making it impossible to prepare a holistic standardized workflow. Where there is a lack of recommendations, we assume that it is possible to follow guidelines normally applied in traditional cartography. The following paragraphs contain examples of these guidelines.

To maintain the legibility of tactile maps, Piątkowski (1969) recommends the following: symbols must clearly contrast with each other, be unambiguous and constructed with the simplest graphic elements possible, but, at the same time, their design should suggest their meaning. Piątkowski recommends defining the minimum allowable radius of curvature for different symbol groups (e.g., lakes, roads) and proposes that the distance between elements forming a texture should be at least three times the thickness of the element.

According to Grygorenko (1970), when mapping land cover elements, the most characteristic breakpoints should be marked first. Then the full borders should be drawn. Appropriate curvature should be maintained to create easily traceable elements. In fact, angular compliance is the most important factor in line symbol

Table 1. Miscellaneous.

Parameter	Values and sources
Orientation mark type and placement	Top right-hand corner of a map (Więckowska *et al.*, 2012) Dotted upper edge of a map sheet (The NSW Tactual and Bold Print Mapping Committee, 2006; Štampach and Muličková, 2016) Line along a north edge (Thompson, 1983; BANA and the CBA, 2010)
Recommended sheet format	Should not exceed the hands' range of a seated user (approximately 50 × 50 cm) (Olczyk, 2014) ISO A3 (de Mello, 2018) For tactile displays (either on a wall or a stand): maximum 60 × 100 cm with 90 cm clearance (for wheelchairs) (ISO, 2016)
Recommended linear scale length	Maximum 5 cm (Więckowska *et al.*, 2012) 2 cm (width of 2 fingers) (Gardiner and Perkins, 2002)
Maximum number of textures on a single map	4 (including plain background) (Więckowska *et al.*, 2012; Červenka *et al.*, 2013) 6 (Regis and Nogueira, 2013; Instituto Nacional de Estadisticas y Geografia, 2017)
Maximum number of distinct symbols on a single map	10–15 (Rowell and Ungar, 2003)

generalization according to Boczar (1977). All lines must intersect at the same angles on both original and generalized maps. The same author also indicates that when generalizing area symbols closed by boundaries, the area of the generalized region must be equivalent to the original region, whereas the boundary can be simplified. All of these guidelines could be applied to tactile maps.

During transcriptions of traditional maps into tactile maps, eye and finger resolutions have to be considered, but in such cases, a simple reduction of the amount of information is not the same as reducing the value of information. Reducing the quantity usually leads to an improvement in the quality of its reception (Ratajski, 1989). With this in mind, a numerical generalization parameter proposed by Szaflarski (1955) can be also applied to tactile cartography: the map content reduction ratio should remain close to the square of the scale reduction value. Another example of a numerical parameter is that proposed by Topfer and Pillewizer (1966):

$$n_f = n_a * \sqrt{M_a M_f}$$

where n_f is the number of objects that could be shown in the target scale, n_a is the number of objects shown on original scale, and M_a and M_f are scale denominators of the original and target source respectively.

One of the important problems for the standardization in tactile mapping is that the most common real-world features are symbolized differently on tactile maps in different parts of the world, e.g., sea and ocean waters. A common approach for Polish tactile maps is to use parallel horizontal lines for the symbolization of large water bodies (Główny Urząd Geodezji i Kartografii and Polski Związek Niewidomych, 2006). In Australia, water bodies are presented using dashed horizontal lines (The NSW Tactual and Bold Print Mapping Committee, 2006), whereas on tactile maps originating from the United States, either dotted patterns or slanted parallel lines are used to symbolize the same features (National Braille Press, 2021). As a result, due to this local standardization, PVI accustomed to symbolizing particular features with fixed textures might omit the legend and be mistaken while reading foreign maps. In such cases, it would be useful to follow traditional cartographic rules. Well-established standards, such as those relating to topographic maps, exist in traditional cartography (e.g., Davis *et al.*, 2019). Apart from the official guidelines, numerous unwritten cartographic conventions exist, e.g., water on maps is blue and the forests are green. Thanks to such consistent use of symbols along with their meaning, readers spend less time familiarizing themselves with symbols (Lobben, 2015). Such conventions should also be developed in tactile cartography.

Numerical parameters necessary for the creation of tactile maps

These can be divided into three main groups: dimensions, distances and heights. Many of the parameters cited in Tables 2–4 derive from national guidelines and result from practical experience of tactile cartographers in different parts of the world.

Dimensions (Table 2) are mainly related to tactile symbols. They consider both general parameters and numerical parameters for different geometric symbols (points, lines and areas). In some cases, there is a great discrepancy between the suggested values, e.g., the minimum size of point symbol spans from 3 to 5 mm in the Polish guidelines (Więckowska *et al.*, 2012) to 13 mm in the Brazilian guidelines (Regis and Nogueira, 2013). Such discrepancies may derive from the fact that different production methods were analysed.

Distances (Table 3) refer to the spacing between different types of symbols or their elements. The recommended distances between different symbols range from 1 mm (Wabiński *et al.*, 2022) to 5 mm, as recommended in the Polish guidelines (Więckowska *et al.*, 2012). Interestingly, although both of the values cited above originate from Polish authors, they differ greatly. Similarly, the minimum recommended distances between symbols and their annotations are different depending on the country of origin of the guidelines, e.g., in Polish guidelines one can read that such distances should be at least 3–4 mm (Więckowska *et al.*, 2012), whereas in the US and Canada, these are 3–6 mm (BANA and the CBA, 2010).

The final group of parameters mentioned are those relating to the height of symbols (Table 4). For this also, there is no agreement on the optimal values, e.g., the minimum symbol height should be 0.2 mm according to Jehoel *et al.* (2006), but 0.75 mm according to Jesenský (1988). The same is true for the minimum height difference between symbols: 0.04–0.08 mm according to Jehoel *et al.* (2009), but 0.5 mm in the French guidelines (Bris, 2001).

Differences between production methods

Apart from cartographers' preferences in terms of the design of tactile maps, PVI also have preferences when it comes to production methods, which forms yet another obstacle on the way to tactile mapping standardization.

Table 2. Dimensions.

Parameter	Values and sources
General rules	
Minimum diameter of a hole (concave element)	6 mm (Bris, 2001)
Minimum size difference between symbols	At least 25–30% between the same geometry symbol (BANA and the CBA, 2010)
Point symbols	
Optimal point symbol size	3–5 mm (Więckowska *et al.*, 2012) 4–6 mm (The NSW Tactual and Bold Print Mapping Committee, 2006) 6 mm (BANA and the CBA, 2010) 10 mm (ISO, 2019) 2–13 mm – bigger points can be mistaken with areas (Regis and Nogueira, 2013)
Minimum point symbol width (construction line)	0.4 mm (Bris, 2001)
Line symbols	
Minimum line symbol length	12.5 mm (BANA and the CBA, 2010; Štampach and Muličková, 2016) 13 mm (Edman, 1992; Regis and Nogueira, 2013) 13–25 mm – depends on the texture used (James and Gill, 1975)
Optimal line symbol width	0.5–0.8 mm (Wiedel and Groves, 1969; Polak and Olczyk, 2010) 0.5–3.0 (ISO, 2019) Maximum 2.2 mm (Jehoel *et al.*, 2006) FOR lines thicker than 2 mm, double lines should be used (The NSW Tactual and Bold Print Mapping Committee, 2006)
Area symbols	
Minimum dimensions of area symbol	50 × 50 mm (Edman, 1992) 0.5 in^2 (Heath, 1958)
Minimum dimensions of area symbol in a legend	13 × 13 mm (Edman, 1992) 20 × 50 mm (The NSW Tactual and Bold Print Mapping Committee, 2006) 25 × 125 mm (BANA and the CBA, 2010)
Inscriptions	
Minimum size of tactile character	15 mm (ISO, 2019)

Table 3. Distances.

Parameter	Values and sources
*Between parts of the same symbol**	2.3 mm (Więckowska *et al.*, 2012)
*Between different symbols***	1 mm (Wabiński *et al.*, 2022) 2.3 mm (Nolan and Morris, 1971) 3 mm (BANA and the CBA, 2010) 5 mm (3 mm for highly contrasting symbols) (Więckowska *et al.*, 2012)
*Between 2 lines***	5 mm (Štampach and Muličková, 2016)
*Between 2 parallel lines***	6 mm (James and Gill, 1975)
*Between lines forming double line***	1.3 mm (Jehoel *et al.*, 2006)
Between dots in a dotted line	minimum 2 mm (Więckowska *et al.*, 2012) 0.5–4 mm (Bris, 2001) 20 dots per inch (Wiedel and Groves, 1969)
Between dashes in dashed line	breaks should be half of the size of dashes (Edman, 1992)
Between tributary and the main river	3 mm (Więckowska *et al.*, 2012)
Between symbol and its annotation	3–4 mm (Więckowska *et al.*, 2012; Červenka *et al.*, 2013) 3–6 mm (BANA and the CBA, 2010) 6 mm (ISO, 2016)

* Maximum.
** Minimum.

Table 4. Heights.

Parameter	Values and sources
Minimum height difference between symbols	0.04–0.08 mm (Jehoel *et al.*, 2009) 0.5 mm (Bris, 2001)
Maximum number of height levels on a single map	5 (Bris, 2001)
Recommended heights for symbol types	Braille: 0.5 mm, line and area: 1 mm, point: 1.5 mm (Wiedel and Groves, 1969)
Minimum symbol height	0.2 mm (Jehoel *et al.*, 2006) 0.4 mm (Bris, 2001) 0.5 mm or 0.3 mm for smooth symbols (ISO, 2016) 0.75 mm (Jesenský, 1988)
Optimal symbol height	0.3–1.5 mm (ISO, 2019)

In a study by Nagel and Coulson (1990), participants indicated the superiority of swell paper over multi-textured and thermoform maps, whereas in (Pike *et al.*, 1992) no significant differences in performance were found between the same two methods. In the two papers that investigated this issue (Jehoel *et al.*, 2005; Wabiński *et al.*, 2022), the majority of participants preferred the rougher substrates (textures) over the smoother ones used for area symbols.

Most of the sources cited here do not provide detailed information about the recommended symbols, but some indicate explicitly the production methods to be used along with the guidelines. For example, these include the Australian (The NSW Tactual and Bold Print Mapping Committee, 2006) and Swedish (Eriksson *et al.*, 2003) guidelines that relate strictly to the swell paper method or the guidelines specifically created for thermoformed tactile maps (Gardiner and Perkins, 2002).

When choosing appropriate production methods, apart from the specific design guidelines, one has to consider production-related issues. For example, in the swell paper method, raised elements tend to widen when overheated, whereas in thermoforming, the dimensions of the final product differ from those of a mould due to the width of the PVC (polyvinyl chloride) foil used for production. We assume that the numerical values provided by other authors cited in this paper refer to the final products, regardless of the production methods used, because these authors do not provide such details. The future standardization guidelines should specify the range of production methods for which the guidelines apply.

Discussion and conclusions

As noted by Wiedel and Groves (1969), symbolization must be standardized in order to facilitate the design and use of tactile maps. Considering the recommendations described in this paper, selected aspects of tactile mapping can be standardized, but to obtain a holistic solution, much work is still required.

Currently, official bodies issuing tactile maps usually produce high quality and widely accepted tactile maps, but due to the old-fashioned manual workflows they maintain, their production is slow and expensive. On the other hand, numerous solutions for automatic tactile map development have emerged. The problem with such solutions is that these products does not involve appropriate generalization and adaptation of the spatial data that they rely on, or their creators spend much time seeking appropriate design solutions instead of applying ready-to-use guidelines and parameters. Leonard and Newmann (1970) highlighted the need, that is still relevant, to develop solutions using standardized procedures that could be applied locally at low cost and without specialist equipment. A combination of automated workflows for the creation of tactile maps and modern production techniques along with parameterized design rules might result in wider access to legible tactile maps and increase their usage among PVI. The more accurate and cartographically sound these products will be, the better.

Our review shows that much has already been done in the parametrization of key stages involved in tactile mapping processes. Unequivocal rules, along with measurable parameters related to symbolization and map editing, can be found in published research. In this paper, we have gathered detailed guidelines for the design of tactile symbols, recommended symbol sets, and the numerical parameters that should govern the preparation of tactile maps, to answer the research questions stated. It is worth noting that many of the most useful, explicit rules come from the less official guidelines, which are based on ther practical knowledge of their creators who have usually verified them experimentally with PVI. Therefore, a more comprehensive knowledge of tactile mapping requires the dissemination of unpublished guidelines and best practices.

This review also highlights a number of problems on the way to the standardization of tactile map production. First of all, the parameters provided in this manuscript tend to differ greatly across various literature resources. One of the reasons is that these resources consider different production methods. The problem is that it is rarely explicitly stated which production methods should be used along with particular guidelines. Even when following unequivocal standards during tactile map compilation, the final result might differ depending on the production method used. Besides, not all shapes can be reproduced using every production method. Thus, readers should consider the parameters quoted as approximate values that should be modified in iterative experiments with different production methods and test with target groups of readers, bearing in mind that PVI feedback is more useful than that of a sighted person. As stated by Stangl and Yeh (2015), they know exactly, what are their needs. Such experiments might allow creating a 'pool' of tactile symbols useful in different contexts as suggested by Jansson (1987). Moreover, such sets should be described in detail, including the production method used. It is not sufficient to describe only 2D properties of tactile symbols when attempting to standardize them. Different production methods might elevate those 2D symbols in different ways, resulting, for example, in varying cross-sections that should also be considered.

According to James (2009), the lack of agreement upon symbology for navigational maps came from the lack of standardized materials for tactile map production, rather than from other considerations. Perhaps, instead of developing numerous new production methods, we should choose one globally recommended method and implement its standardization. Eriksson *et al.* (2003) named the differences between production methods as the largest difficulty in the standardization of tactile symbols. At the same time, as noted by James (2009): standardization should not necessitate stagnation of ideas for improving production methods.

Another problem identified in this paper is local standardization. Some symbols' designs are well established within single countries or regions, but can have completely different meanings in other parts of the world. We therefore need global standards. Such standards exist in traditional cartography, e.g., water is blue on topographic maps. But not only geometric symbols require standardization. Due to the decrease in Braille literacy among PVI (Danish Association of the Blind, 2018), it would be helpful to develop linguistically independent, standardized inscriptions.

Lastly, guidelines for the design of tactile maps seldom form official publications that are translated into English, which reduces their accessibility. There are experienced practitioners who may retire without passing their knowledge and skills on to the next generation of cartographers of tactile maps. For this reason, we plan to create an experience exchange platform for practitioners and tactile mapmakers, where all the guidelines will be stored, and will be available for anyone interested in creating their own, legible tactile maps.

In this paper, we have focused primarily on the haptic content of tactile maps, but due to the rising popularity of multimodal maps involving multiple senses (Brulé *et al.*, 2016; Giudice *et al.*, 2020; Matsuo *et al.*, 2020; Barvir *et al.*, 2021) and universal design concepts in general, future research could address the challenge of formally describing design principles to consider senses other than touch.

To sum up, we would like to paraphrase one of our questionnaire respondents. We believe that in the near future all countries will follow the same rules for the design of tactile maps, which lies in contrast to the current situation where every study - as well as every country - follows different design principles for their creation.

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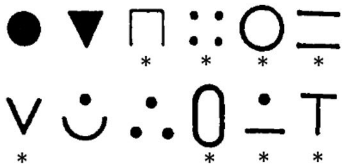
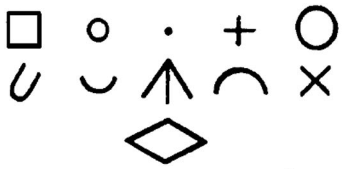
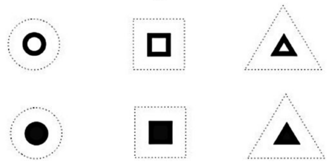
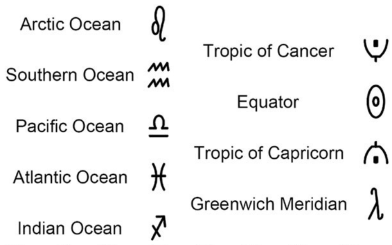
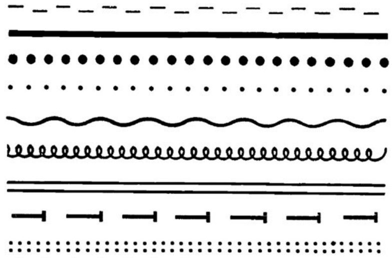
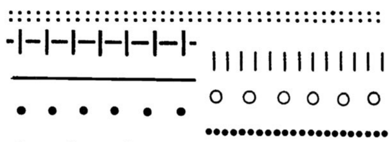
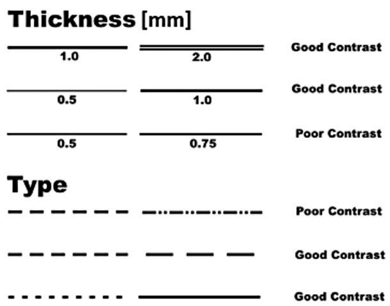
Appendix – recommended symbols

Symbol type	Source	Details	Exemplary symbols (not in scale)
Points	(Nolan and Morris, 1971)	Highly distinguishable[1] point symbols produced using vacuum-formed plastic.	
	(Nolan and Morris, 1971)	The symbols shown, produced using vacuum-formed plastic were tested in 2 sizes: small (0.15 in) and big (0.20 in). For a larger set, all of the symbols were highly distinguishable[1], whereas for the smaller set, those marked with asterisk were considered as highly distinguishable[1].	
	(Nolan and Morris, 1971)	Highly distinguishable[1] point symbols produced using paper embossing.	
	(The NSW Tactual and Bold Print Mapping Committee, 2006)	Point symbols recommended for general use along with the proportionally drawn offsets that must be left blank.	
	(Regis and Nogueira, 2013)	Proposition of standardized point symbols for global features to be used on small-scale maps.	
Lines	(Nolan and Morris, 1971)	Highly distinguishable[1] line symbols produced using vacuum-formed plastic.	
	(Nolan and Morris, 1971)	Highly distinguishable[1] line symbols produced using paper embossing.	
	(BANA and the CBA, 2010)	The set of recommended and highly distinctive line textures.	
	(The NSW Tactual and Bold Print Mapping Committee, 2006)	Recommendations for line symbols design to maintain good contrast between similar symbols on swell paper maps[2].	

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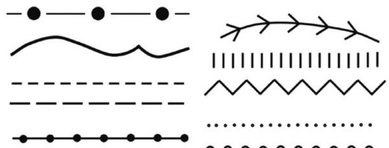
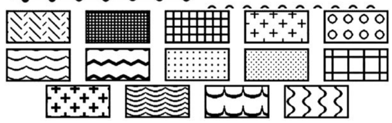
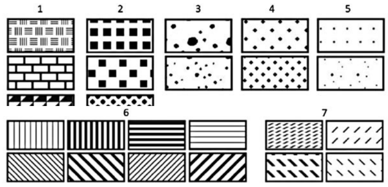
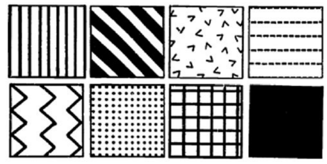
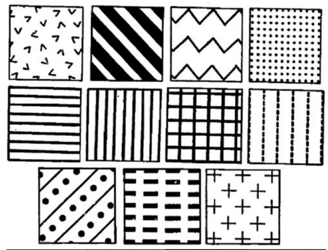
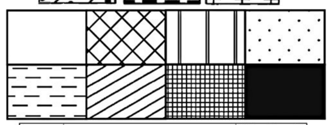
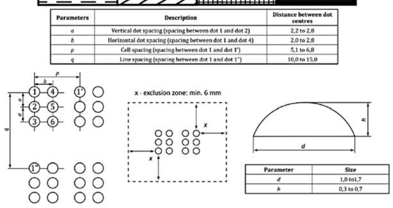
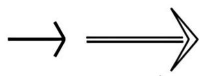
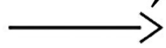
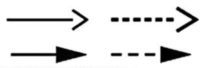
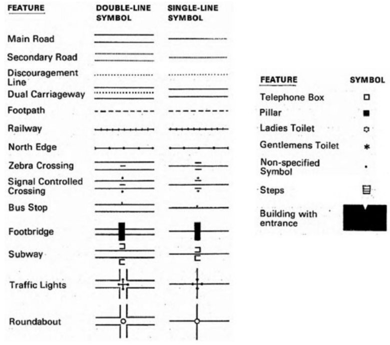
Continued.

Symbol type	Source	Details	Exemplary symbols (not in scale)
	(The NSW Tactual and Bold Print Mapping Committee, 2006)	The set of distinguishable line symbols on maps prepared with the swell paper method[2].	
Area	(BANA and the CBA, 2010)	The set of textures that can be used freely on maps prepared with the swell paper method.	
	(BANA and the CBA, 2010)	Only 1 texture from each of the presented groups can be used on maps produced using the swell-paper method.	
	(Nolan and Morris, 1971)	Highly distinguishable[1] area symbols produced using the Virkotype (discontinued) printing method.	
	(Nolan and Morris, 1971)	Highly distinguishable[1] area symbols produced using vacuum-formed plastic.	
	(The NSW Tactual and Bold Print Mapping Committee, 2006)	Recommended textures for area symbols on maps produced using the swell-paper method[2].	
Inscriptions	(ISO, 2013)	Recommended design and dimensions of braille writing. Dimensional parameters of braille shall reflect the technical correlations between the individual parameters. For example, if the smallest dot diameter and dot spacing are chosen, all other dimensions shall be proportional.	
Arrows	(The NSW Tactual and Bold Print Mapping Committee, 2006)	The minimum shaft length should be 20 mm, arrowhead should form a wide angle (90–150°) and arms should be at least 6 mm long.	
	(Więckowska *et al.*, 2012)	Arrowheads should be in a form of a triangle with a 3 mm distance from tip to end of arrowheads. They should not be presented as solid (filled) triangles.	
	(BANA and the CBA, 2010)	Recommended arrow styles.	
Miscellaneous	(James, 1975)	The first described attempt to create a standardized set of tactile map symbols using vacuum-formed plastic along with suggested meanings. The discouragement line suggests a line not to be crossed to prevent hazardous situations. Non-specified symbol meaning may be adapted depending on the map's topic. It has to be explained in the legend.	

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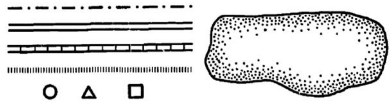
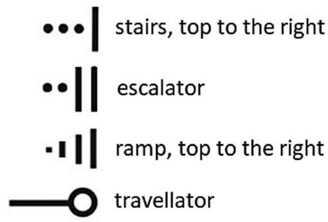
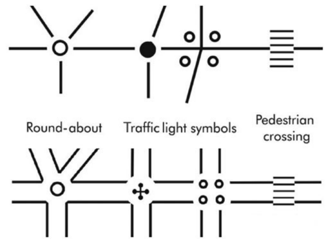
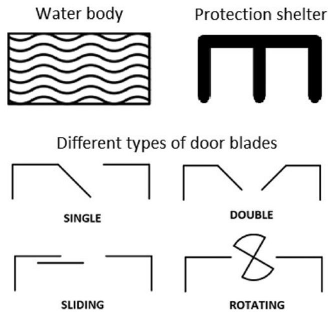
Symbol type	Source	Details	Exemplary symbols (not in scale)
	(Wiedel and Groves, 1969)	The set of symbols that were found the most discrete tactually in the study on vacuum-formed tactile maps.	
	(The NSW Tactual and Bold Print Mapping Committee, 2006)	Recommended symbols for floor plans. Although commonly used in the country of origin, they must always be identified in the map legend.	
	(The NSW Tactual and Bold Print Mapping Committee, 2006)	Recommended symbols for roads (single or double lines) and related infrastructure.	
	(ISO, 2016)	The source provides examples of German and Swedish tactile symbols used mainly for orientation and navigation. Selected examples are presented.	

[1]Criteria for a symbol to be considered highly distinguishable: (1) average confusion with other distinguishable symbols ≤5%, confusion with itself and other distinguishable symbols ≤10%.

[2]The printing method is not explicitly indicated in the source.

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Review

Automatic (Tactile) Map Generation—A Systematic Literature Review

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Abstract: This paper presents a systematic literature review that reflects the current state of research in the field of algorithms and models for map generalization, the existing solutions for automatic (tactile) map generation, as well as good practices for designing spatial databases for the purposes of automatic map development. A total number of over 500 primary studies were screened in order to identify the most relevant research on automatic (tactile) map generation from the last decade. The reviewed papers revealed many existing solutions in the field of automatic map production, as well as algorithms (e.g., Douglas–Peucker, Visvalingam–Whyatt) and models (e.g., GAEL, CartACom) for data generalization that might be used to transform traditional spatial data into the haptic form, suitable for blind and visually impaired people. However, it turns out that a comprehensive solution for automatic tactile map generation does not exist.

Keywords: generalization; algorithm; model; map automation; tactile maps; maps for blind and visually impaired

1. Introduction

We are living in the Information Age—searching, browsing, downloading and archiving data is almost unlimited. This is owed to wide public access to the Internet. Besides, people simply want to know more about their environment and the world that they are living in. Much data has spatial reference and the best way to present that kind of data are maps. They have been used for thousands of years for multiple purposes, such as spatial planning, geology, forestry, and navigation [1].

Today, mainly digital maps are used. Such maps can be edited easily, and it is possible to generate them automatically or semi-automatically. In order to do that, it is necessary to use appropriate generalization algorithms that will allow developing a readable digital map and a smooth transition between scales. The generalization process is not linear and its results cannot be predicted only based on initial data and a set of rules or constraints. The final outcome is a consequence of numerous dynamic variables such as data richness, level of formalization and fuzziness of specifications [2]. Spatial data generalization is even more complicated in the case of tactile maps which are read using the sense of touch or, to a limited extent, using eyes [3].

The overall goal of this work is to provide an objective summary of the current state of research concerning automated map generation in general, but with particular emphasis on tactile maps. To the best of our knowledge, no significant literature reviews on this topic exist. However, as we will demonstrate in this article, there are numerous studies that deal with automatic map generation and many of them focus precisely on tactile maps. The reviewed articles allow us to draw certain conclusions regarding the potential of automatic (tactile) map generation; specifically the problems that have already been solved and the nature of the remaining challenges.

1.1. Background of Tactile Maps and Automatic Map Generation

Most people read maps using the sense of sight, which is the most natural way to perceive them. Unfortunately, disabled people who perceive the world with different senses cannot use them, so they cannot take full advantage of the Information Age. This group includes the blind and visually impaired. According to the World Health Organization 253 million people in the world are visually impaired, of which 36 million are blind and 217 million have moderate to severe vision impairment [4]. This is why we need to present spatial data in a form that is suitable for these people. One way of achieving this goal is to produce tactile maps. The main difference is that a sighted map user can cover the whole map sheet at once with his or her eyes, while a person with visual impairments has to read the tactile map fragment by fragment and must build up an image of the whole map in his or her memory [5]. However, apart from the differences resulting from the sense used to perceive the map, there are other characteristics of blind and visually impaired people that designers have to take into consideration. For example, blind and visually impaired people who suffer from diabetes have decreased tactile sensitivity and thus require different materials than those with high tactile acuity [6]. Simple conversion of the visual image into tangible form, regardless of the methodology used, would most probably lead to meaningless output [7]. Thankfully, along with the growing social awareness of the problems of disabled people, an increasing number of materials and solutions making their lives easier are appearing.

The first tactile maps were developed in the 18th century [8]. They were handcrafted for personal needs. Today tactile maps are usually printed with use of specific techniques that allow mass production, but the process of their creation is still expensive and time-consuming. The techniques that are currently used to produce these maps are suitable for production in large quantities. Thus, printing single copies of unique tactile maps is usually out of reach of those interested. Besides, developing a tactile map requires a team of specialists: tactile cartographers, tactile graphic designers, relief printing specialists and, when a map is designed to be used in schools, teachers and their pupils to validate its utility.

The Braille Authority of North America and Canadian Braille Authority [9] presented an overview of methods that are currently used to produce tactile maps. One of these methods involves embossers (e.g., Tiger, ViewPlus) to create tactile graphics from digital files. Embossed braille graphics can be produced easily and do not require physical masters, but at the same time, there is little variation in height between specific symbols and the number of possible textures that may be obtained is limited. Another production method is microcapsule graphics. They are printed on special microcapsule paper that are then extruded by heating its surface by a device called "enhancer." This method does not require physical master and graphics can be altered or duplicated. However, this technique requires many trials in order to achieve the desired results (e.g., appropriate extrusion heights). Besides, the microcapsule paper is rather expensive and can be damaged easily. Vacuum-formed graphics require a hard copy master. This method is preferred by many tactile map users due to its quality, but the production process is costly and time-consuming [10]. The aforementioned methods are well-established in the tactile map production industry but new solutions keep emerging, such as 3D printing [11], which is suitable for producing single copy maps at relatively low cost.

A new trend in tactile map production involves audio feedback. The ATMAPS Consortium, which consists of several European universities, public institutions, and a private company, is responsible for the project, whose main goal was to specify the audio, tactile and audio-tactile symbols that could be used in audio-tactile maps. Its results are described in a number of reports that can be found on the project's website [12]. Not only did the Consortium define standards for symbolization and map composition for five types of audio-tactile maps, but it also prepared an atlas of Europe that consists of 34, ready-to-print tactile maps (AT-atlas).

Apart from "static" techniques, there are a number of refreshable touch display technologies. They can be modified on-the-fly and often provide audio, vibration or haptic feedback [13]. These interactive solutions involve finger tracking systems or use touch-enabled surfaces [14]. A nice overview of refreshable touch displays was presented by O'Modhrain et al. [7]. However, all these methods might benefit from improvements in production processes.

Standardization of tactile symbols might be a good first step to optimize the tactile map production process. Lobben and Lawrence [15] proposed a standardized set of tactile symbols designed for printing on microcapsule paper and made them available for free. Unfortunately, every printing technique requires different parameters of tactile symbols. This is why the development of a completely universal tactile symbols set might be impossible. Besides, tactile maps often require a decent degree of map content generalization and proper placement of symbols and labels. An average human without any visual impairment, under normal lighting conditions and at a viewing distance of 50 cm, can distinguish two points or lines as separate if they are at least 0.15 mm apart from each other [16]. To distinguish two points as separate with use of touch, they have to be at least 2.4 mm apart from each other [17,18]. Cartographic signs commonly used in traditional cartography are usually too small or too complicated to be read correctly using the sense of touch or a damaged sense of sight, even after raising them to a spatial form. This makes tactile maps less detailed and thus requires printing in larger formats [19].

However, the format of a tactile map is determined by the maximum reach of the user's arms. According to the survey results [20] the maps produced in the form of single sheet are more readable than those consisting of several parts. The aforementioned survey also deals with the topic of the maximum number of tactile signs that can be used on tactile maps. Map producers use 10 to 15 different signs on one map, out of which 6–7 are point signs, 3–4 are line signs and further 3–4 are surface signs (textures). When we compare these numbers with standards for classic map generation, the level of generalization required for tactile maps generation becomes even more evident. To facilitate map content distinction, tactile symbols should vary in height. According to widely-accepted standards [19], surface signs should be the lowest (0.5–1.0 mm), line signs moderate (1 mm), with point signs being the highest (1.5 mm). Braille characters have to be standardized. The most popular standard in Europe is the Marburger Medium Parameter, where the height of a Braille dot should fall between 0.5 and 0.8 mm.

Despite all the requirements mentioned above, a tactile cartographer has to bear in mind that the legibility of a tactile map is of the highest priority. Thus, tactile maps should meet the requirements related to tactile graphics design in the first place. The adherence to mathematical and cartographic principles is less important. An important step in the tactile maps production process is the end-user evaluation. The user feedback will vary depending on the test group characteristics and preferences, but it may prove invaluable in the process of proper tactile maps design.

On the other hand, access to spatial data has never been easier. Geoportals, spatial and statistical data, and software dedicated to map production—all these can be found on the Internet. However, cartographic skills are essential to produce correct maps manually, in contrast to automatic map generation. This process is also called "on-demand mapping" and described as automatic derivation of maps tailored to requirements expressed by users [21]. As stated by Armstrong [22], in the traditional map production process, the cartographer serves as the active agent. Even if a map is created automatically out of the set of spatial data, the cartographer has to iteratively modify it in order to achieve specific map user requirements. By having the data appropriately generalized in the first place, the automation of map production would be easier.

According to [23], "map generalization is a process of effective portraying changing levels of detail among geographic phenomena in order to reveal their various properties." Thus, cartographic generalization is used for transforming the original spatial dataset into maps of smaller scale. This involves changing the representation of spatial features and their placement on a map. Manual generalization is time-consuming and dependent on cognitive and technical skills as well as subjectivity of cartographer. The automation of this process speeds up map production and allows keeping all the maps up to date [24].

Automatic map generation is not a new research field [25–28]. However, it still requires a systematic review to provide a comprehensive summary of currently existing literature in this field. This particular review was prepared to obtain insight into the current state of research of automatic (tactile) map generation: methods, tools, and input data sources as well as the existing solutions. The results might be interesting not only for practitioners of cartography, but also for everyone else willing to involve maps in their daily work for spatial data representation. Today, due to democratization of cartography, everyone is a cartographer and can make his or her own maps [29]. Researchers, on the other hand, might learn about the current state of technology and find inspiration for future research.

1.2. Existing Literature Reviews and Motivation

We conducted a non-systematic keyword search in the libraries of selected journals, with the aim to find existing systematic literature reviews regarding automatic (tactile) map generation. The term searched was "systematic literature review" in a list of 30 journals.

This methodology allowed us to identify 20 literature reviews. Most of them are literature surveys and basic non-systematic reviews. However, based on their screening we decided to distinguish three systematic literature reviews. They are related to GIScience, cartography, remote sensing and climate change [30–32]. These reviews were used as sources of good practice examples for this particular systematic literature review. As none of them comply with the topic of automatic (tactile) map generation, they are insufficient to provide answers to general questions that were the motivation to take the presented research:

- What are the latest achievements and innovations in this field?
- What are the gaps in current research (if any)?
- Who currently conducts research on automatic (tactile) map generation?

A classic, non-systematic literature review would be insufficient to answer these questions, as it is usually of little scientific value and cannot be recreated. A systematic review synthesizes the existing works in a fair manner, as the review should be undertaken in accordance with a predefined search strategy, which ensures the completeness of the search [33]. A systematic review is an overview of primary studies, containing a clear statement of the objectives, materials, and methods and it is conducted according to explicit and reproducible methodology. Besides, as opposed to regular (journalistic) literature reviews, it includes results that might contradict the stated hypothesis [34].

2. Review Methodology

The main goals of this study are to review the possibilities of automatic map generation, especially tactile maps, as well as various concepts of data generalization. The review follows general systematic literature review guidelines [33]. Our review began with the development of a review protocol (Supplementary material). It specifies the background of the project, describes the inclusion/exclusion criteria, search strategy and methodology of data extraction, as well as the methods to synthesize and report results.

We started the review by defining clear and precise research questions, which enabled proper selection of primary studies [35]. The main task during automatic map generation is to use proper generalization algorithms and models (RQ1). Generalization might not be essential if there is good input data (RQ3). We were also interested in already existing solutions for automatic (tactile) map generation (RQ2). Taking the above into consideration, the following research questions were defined:

- RQ1: What are the generalization methods and models for automatic tactile/thematic/background map generation?
- RQ2: What are the existing systems and solutions allowing automatic (tactile) map generation?
- RQ3: How to design spatial databases for automatic map generation?

To determine whether primary studies are eligible for the systematic review, we applied the inclusion and exclusion criteria, defined in the Review Protocol.

We applied an iterative search strategy to determine the most suitable set of keywords to be used [33]. This also allowed us to minimize the search bias. The search strings described in the Review Protocol were used to browse seven electronic databases that included all the papers published before 31 June 2018. However, we tried to keep up to date with all the recent works on this subject. This is why we considered all the relevant articles manually gathered and suggested by scientific newsletters of Mendeley, ResearchGate and Tandfonline, even if they were published after the aforementioned date. This resulted in the identification of 646 digital sources (Table 1). All the selected studies were stored and managed within Mendeley Reference Management Software [36]. At the first stage, only title, keywords and abstract were analyzed. Two independent reviewers went through all of them and tagged them adequately using tags described in the Review Protocol.

Table 1. Electronic databases used during the review process (source: own study).

SOURCE	URL	DATE OF SEARCH	SEARCH RESULTS
FREEFULLPDF	http://www.freefullpdf.com	1 August 2018	38
GOOGLE SCHOLAR	http://scholar.google.com	31 July 2018	137
IEEE LIBRARY	http://www.ieeexplore.ieee.org	1 August 2018	85
SCOPUS	https://www.scopus.com	31 July 2018	176
SPRINGER	https://link.springer.com	1 August 2018	48
WEB OF SCIENCE	http://www.webofknowledge.com	31 July 2018	75
WILLEY ONLINE LIBRARY	http://onlinelibrary.wiley.com	1 August 2018	31
OIN WAT *	n/a	13 August 2018	29
SCIENTIFIC NEWSLETTERS	n/a	n/a	51

* Scientific Information Center of Military University of Technology in Warsaw.

Primary studies included by both reviewers were moved to quality assessment. Every inconsistency between the reviewers' choices was discussed. Thanks to these steps a set of 45 primary studies was selected for further analysis. An online spreadsheet that contains study quality assessment tables and data collection forms was developed for each of the primary studies (cf. Review Protocol). Papers that did not meet the criteria of minimum points for quality assessment were excluded. The same applies to papers that turned out to be completely irrelevant after full-paper screening, which was true for 11 papers.

After identifying the appropriate documents in online libraries, an iterative backward reference search was conducted in order to identify additional primary studies related to the topic of this review [35]. This resulted in 33 primary studies that went through full-paper screening. Only 11 of them complied with the inclusion criteria. Finally, 55 primary studies that show relevance to the research questions stated were selected for the review (Figure 1).

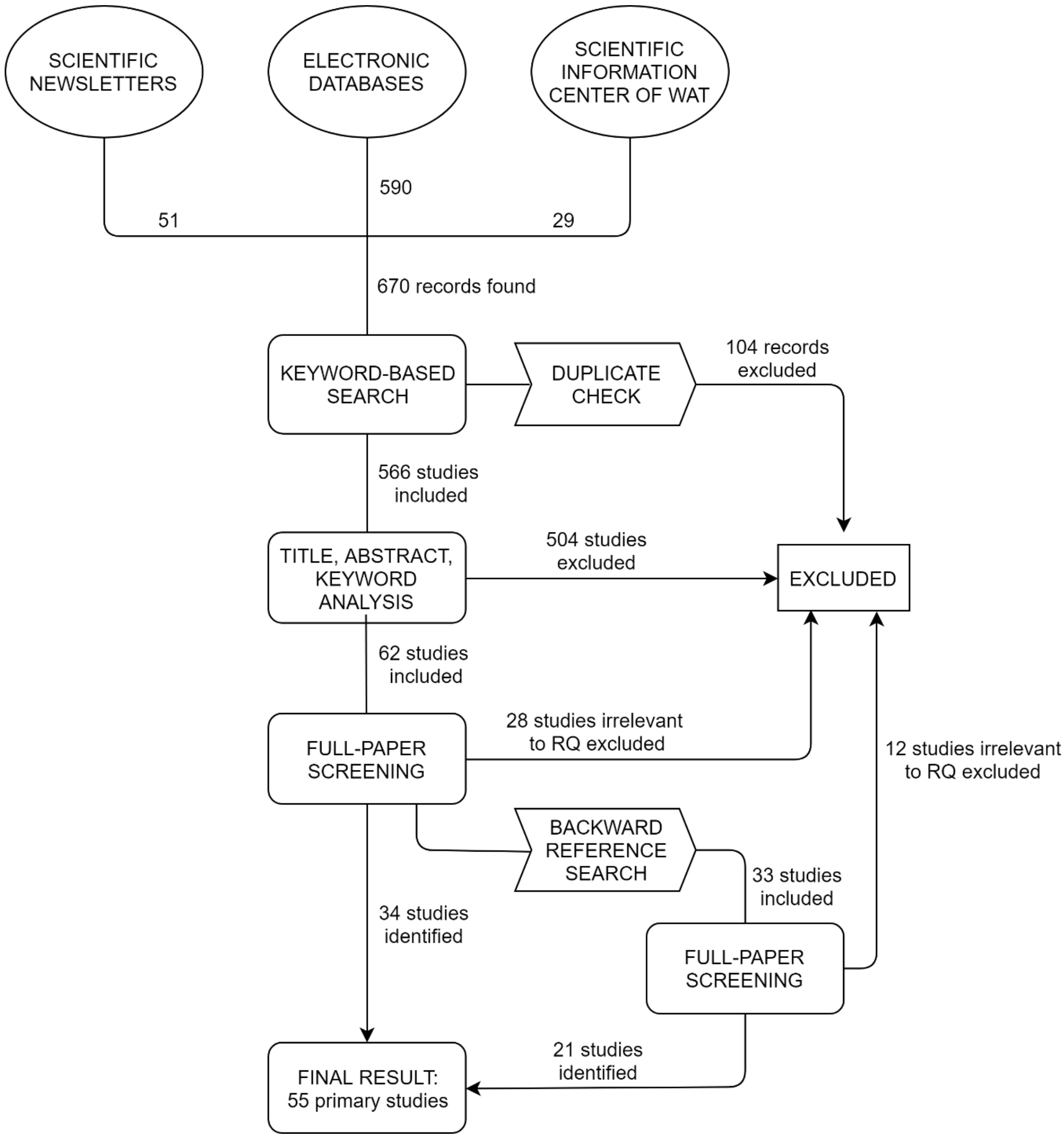

Figure 1. The course of the selection process together with the number of included and excluded papers in each step (source: own study).

3. Review Results

After a detailed analysis of the identified primary studies we can agree with the statements that appear in most of the articles, pointing out that automatic generalization processes are important in terms of automatic generation of both traditional and tactile maps [37–39]. It can also be noted that automatization of cartographic processes, which seemed impossible a few years ago, is now being successfully implemented in many countries.

The analysis of the year of publication of all identified papers did not reveal a clear trend (Figure 2). This applies to both the initial set of 566 identified works and the final set of 55 primary studies chosen for qualitative evaluation. Publications from 2019 were not covered in the systematic search and thus only five papers from this year were considered in this review.

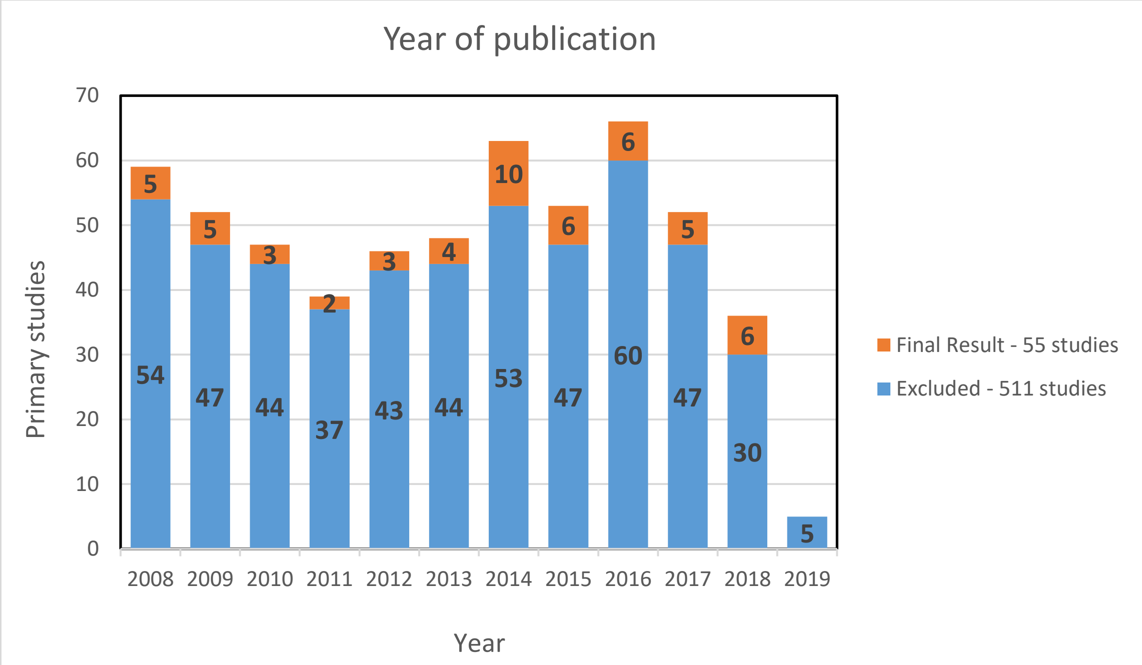

Figure 2. Relation between publish year and number of papers (source: own study).

During full-paper screening the tags were used to determine which of the stated research questions were answered by particular primary studies (cf. Review Protocol). More than half of the selected primary studies provided answers to RQ1, while 40% of them presented the existing systems and solutions in the field of automatic (tactile) map generation, providing answers to RQ2. Around one-third of papers presented good practices regarding spatial database design for automatic map generation, which was the answer to RQ3 (Figure 3).

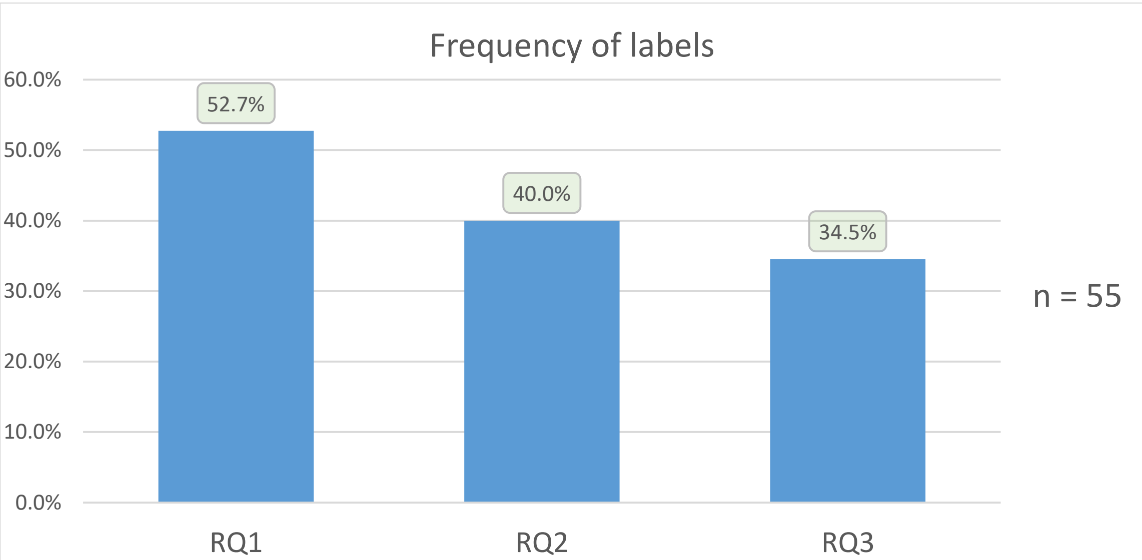

Figure 3. Number of primary studies providing answers to particular research questions (n—selected primary studies) (source: own study).

The associations between specific terms appearing most frequently within 55 selected primary studies were investigated, using weighted network visualization (Figure 4). This analysis was prepared in VOSviewer 1.6.9 using fractionalization method for normalizing the strength of the links between items [40]. The bigger the label, the higher the weight of certain terms. The colors are determined by the cluster to which the term belongs, while lines represent links: the closer two terms appear, the stronger correlation between them exists. There are four clusters with the term "map" appearing most frequently across primary studies. The term "generalisation" appears very close to both "model" and "algorithm." "Map generalization" of "topographic data" is closely related to "scale" transitions, while the "tactile map" is correlated with people (users). Different spellings of the same words were not unified—this is why "generalization" and "generalisation" coexist in the figure.

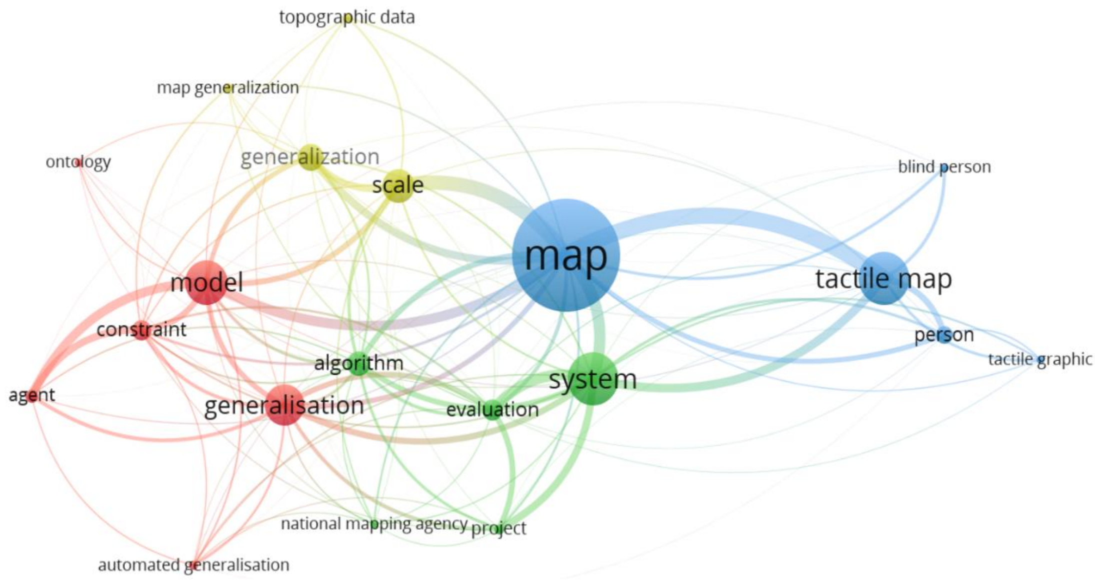

Figure 4. Weighted network visualization of associations between terms within identified primary studies (source: own study).

3.1. Research Question 1—What are the Generalization Methods and Models for Automatic Tactile/Thematic/Background Map Generation?

"Generalization methods and models for automatic map generation" was the most popular topic among the identified papers. Table 2 summarizes information regarding the identified generalization algorithms and models. It also provides a brief description of these studies. While preparing this section we were considering all appearances of the interesting features (algorithms, models, and operators) in the text. Not all tagged studies were included in the table.

We managed to extract many algorithms that can be used for the generalization of spatial data. *Douglas–Peucker* along with *Visvalingam–Whyatt* are well-known algorithms for simplifying line objects that appeared frequently across the studies [29,41]. The first one focuses on choosing line vertices to keep in the generalized version (bases on linear offset of each vertex), while the latter selects the ones to be deleted (uses area of displacement of each vertex). As a result, *Visvalingam–Whyatt* algorithm produces less angular results. The *elastic beams algorithm* for managing overlapping symbols treats linear features as elastic bars that bend if conflicts are detected [42]. *Skeletonization* that approximates medial axis for transformation of polygons into polylines [43], and *least-squares adjustment* is used for generalization in constraint-based approach where residuals are evenly distributed [44]. Other authors proposed modifications of existing solutions such as the *Douglas–Peucker–Peschier* algorithm [45], *combined stroke-mesh algorithm* for automated road selection during map scale transformations [46] or *collaborative displacement method* that combines aggregation, elimination and constrained reshape for building generalization in urban area maps [47]. In the given set of primary studies, we also identified proprietary solutions such as an algorithm for generation of abbreviated street names that was implemented because the names of features were too long to be placed on tactile map (written in Braille) [48]. A long list of algorithms for the optimization of label placement, such as the algorithm for labelling islands by placing words outside their polygonal extent, as well as those for the simplification and smoothening of spatial features is presented by Reimer [49]. Takagi and Chen [50] described two additional algorithms that are useful for automatic map generation: *Hilditch's thinning algorithm* that obtains skeletons of scanned objects, which are then used for automated detection of hand-drawn features, and *Mamdani's fuzzy interference* used in the proposed system to design classification methods of the detected features.

The automatic generalization processes require a lot of computational power. The two most popular approaches for map generalization process distribution are *regular partitioning* and *geographical partitioning*. They are discussed in Berli et al. [51]. The first one is quicker, but it takes no contextual information into account, while the latter is less efficient in terms of running time, but results integrate the geographical context and in effect, is more accurate. The generalization models described in next paragraphs usually use one of these approaches.

Different generalization models are proposed across the reviewed literature. Some of them are purely conceptual, e.g., the *Pseudo-Physical Model* [52], while others are fully functional and tested solutions with certain applications: *Agent-based, GAEL* and *CartACom*. In the *Agent-based* model, each object of spatial database is considered an agent. This means that every entity of the database operates autonomously (without human intervention) and tries to achieve the desired goal using its capabilities—in this case to generalize itself in order to satisfy its cartographic constraints [53]. There are two levels of agents. A "micro" agent is a single geographic object (e.g., building), while a "meso" (macro) agent is a composition of "micro" or "meso" agents, as for generalization purposes they have to be considered together (e.g., a set of buildings in a neighborhood). This model is best used in dense [54] and well-structured urban areas [39]. On the other hand, the *GAEL* model (*Generalisation based on Agents and Elasticity*) is an extension of the *Agent-based* model for management of background themes such as relief. They differ from foreground themes because they are defined everywhere in the space. There are two types of cartographic constraints in *GAEL*: external, which cause the deformation, and internal, representing the shape preservation. The balance between them is required for successful generalization [55]. *GAEL* is often used for terrain models such as relief or land cover [54]. The *CartACom* model relies on communicating agents and was designed to handle unstructured geographic spaces with no clear borders between groups of objects [56]. Spatial relations between objects are of high importance in this model [57]. The model introduces relational constraints managing relations between two agents. There are three types of them: legibility constraints, constraints of preservation and of geographic coherence [58]. This model is best used for low density [54], heterogeneous rural areas [39]. In Touya and Duchêne [59] the authors argue that it is impossible to solve the generalization problem with a single model. The authors suggest that instead of constantly developing new solutions, one should benefit from the existing models and make them collaborate. This might be done by using the proposed framework—*Collaborative Generalisation*. In this approach specific map parts are treated by certain models that work best in particular cases.

A real issue in multi-scale mapping is the fact that there are two big gaps when changing scales: in terms of content and its representation [60]. This results in orientation problems while zooming in and out. The Authors present a new research project, whose goal is to reduce these problems by adding more intermediate levels (scales) to the already existing multi-scale image pyramid. More or less at the same time, in [61] a vario-scale structure for spatial data allowing zooming in and out smoothly was proposed. The Authors discuss how *tGAP* structure represented by 3D space-scale cube can facilitate continuous generalization.

During the review we counted the appearances of specific generalization operators in studies, using data extraction forms. It turned out that there was a big inconsistency in their naming—the review revealed 38 unique names of generalization operators across all the studies. This is because they come from different taxonomies and, as a result, they can bear various names while meaning the same. On the contrary, the same term may refer to different operators. There are three known operator taxonomies [28,62,63]. These taxonomies use natural language and if one would like to use them for automatic map generation, it would be necessary to prepare formal and unequivocal descriptions of these operators [64]. Figure 5 presents the operators appearing in the identified primary studies normalized to the division proposed by Foerster et al. [63]. The most popular operator is *enhancement* (17% of appearances). It is used to emphasize the message carried by a spatial object in many ways (e.g., enlargement). Two other frequent operators are *displacement* (13%) usually used to maintain sufficient distances between map objects, and *simplification* (12%) for reducing the complexity of objects. *Reclassification* is rarely used (2%), which is understandable in view of the fact that most of the papers were describing generalization within National Mapping Agencies (NMAs), where reclassification of specific objects is undesirable.

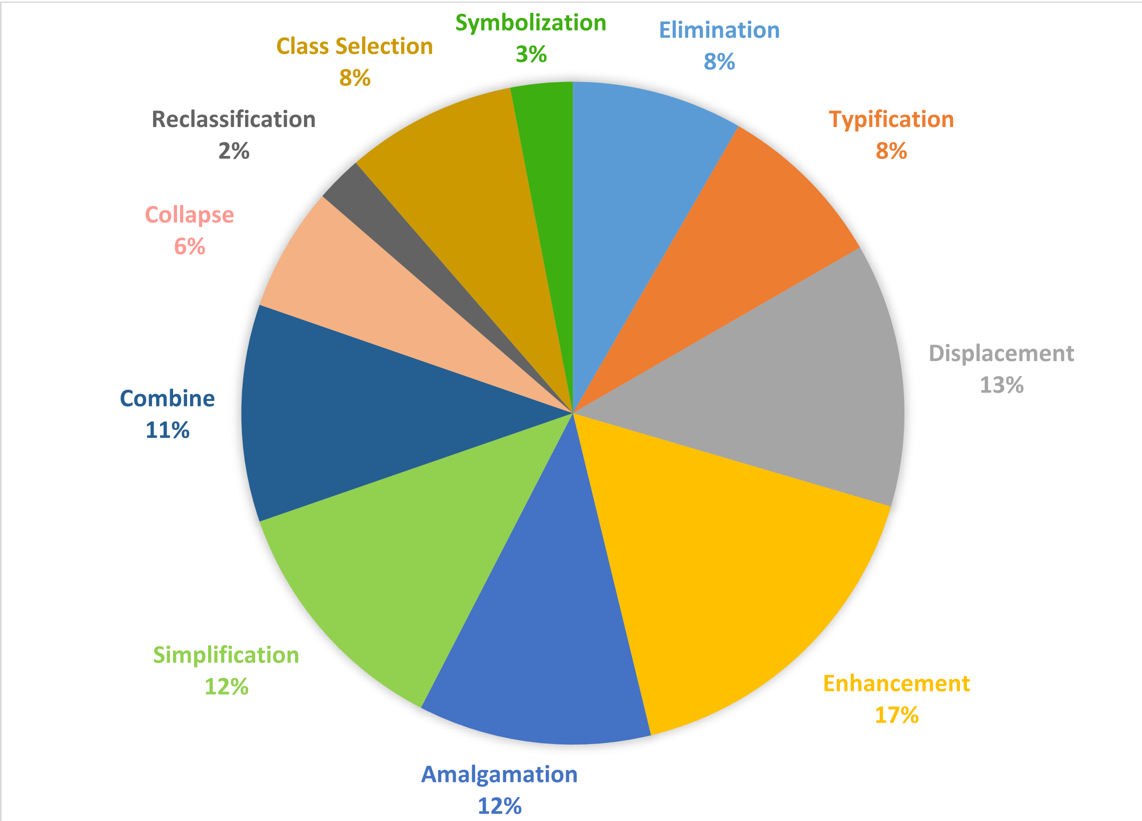

Figure 5. Number of appearances of generalization operators across primary studies (source: own study).

Table 2. Identified generalization algorithms and models (source: own work).

Article	Generalization Algorithms	Generalization Models	Evaluation	Generalization Approach Overview
[37]	n/a	*General multi-scale conceptual model*	Tested on a sequence of maps of the Hunan lake region in China.	The authors propose multi-scale generalization operators. These are instructions for Agent's auto-generalization.
[52]	"Forces" control and determine each object's behavior (e.g., *clustering*, *reshaping*)	*Pseudo-physical model* (electric field theory)	Tested on a set of polyline and polygon objects in an urban area of Haifa in Israel.	The "power" of each object in any map is computed. It produces "forces" that act on objects and control them according to cartographic constraints.
[54]	n/a	*Multi-Agent-System* *CartACom* *GAEL* *Agent-based*	The approach is presented on sample bathymetric data in dedicated software.	Agents access cartographic knowledge stored in the ontology. The agent prepares different generalization plans regarding its environment.
[65]	The paper mentions NMAs that developed their own generalization algorithms, but it does not specify them.	n/a	n/a	Generalization operators used in NMAs in Europe. Which operators work best with certain feature types on maps, taking into account transitions between scales?
[60]	*Morphing of lines*, *continuous deformation of polygons*, *continuous vario-scale generalization*	*tGAP* *Space-Scale Cube (SSC) structure*	n/a	Providing intermediate levels to the multi-scale pyramid might allow smooth zooming and solve the problem of gaps between scales in existing map services.
[43]	*Skeletonization*, *morphological filtering*, *majority filter*, *simulated annealing*, *SVM*, *neural networks*, *fuzzy logic*, *random seed points*	n/a	Sample dataset of the Valencia region in Spain. The automatic method produced different results than the target dataset, but the results are promising.	Automatic generalization of land cover no-gaps polygon data from 1:1k to 1:25k scale. The methodology—several steps of aggregation of various feature types.
[66]	*Least squares adjustment*, *energy minimization*, *simulated annealing*	*Agent-based*	Tested on 99 sample urban blocks of Swisstopo data. Which of the eight tested operators were most frequently executed?	How to optimize a sequence of multiple generalization operators being applied to an entire set of map features? Eight operators in a sequence of maximum 20 steps were used.
[39]	*Least squares algorithm*, *Douglas Pecker*, *Displacement algorithm (CartAGen)*	*Agent-based* *CartACom* *GAEL*	Simple 3D printed map was created manually, followed by an attempt to obtain a similar map with use of automatic operations. The map was evaluated by experts.	Main research issues regarding models for automatic tactile map generation were identified. The authors concluded: no examples of automatic generalization, schematization and labelling in automatic tactile cartography.
[49]	A number of search algorithms are mentioned and others: *Rotating calipers*, *Visvalingam–Whyatt*, *Douglas–Peucker*, *Imai–Iri*, *Reimer–Meulemans*	*Sliding label*, *fixed position label models* Author's multi-criteria model for point feature labelling	Author tests his algorithm for labelling different types of features and then compares the results with manually generated labels.	Analysis of cartographic design principles for automated map generation. It focuses on map features labelling and proposes a model for this task that follows defined requirements and constraints.
[59]	*Simulated annealing*, *elastic beams*, *least squares algorithm*	*Agent-based* *GAEL* *Haunert*	Tested on very diverse sample data in France, coming from the "Official Publication N^{o} 58 of Euro-SDR project."	The authors propose "Collaborative Generalisation" (CG). Instead of creating models from scratch; they would like to see the existing models work together.
[67]	*Elastic beams*	*Agent-based* *CartACom* *GAEL*	n/a	Automated generalization of vector data is based on synergy between three existing multi-agent generalization models: AGENT, CartACom, GAEL.

Table 2. *Cont.*

Article	Generalization Algorithms	Generalization Models	Evaluation	Generalization Approach Overview
[41]	*Douglas–Peucker*, *Visvalingam–Whyatt*	*Constrained tGAP*	Comparison of 1:10k scale data from constrained tGAP and existing 1:10k database. A number of issues were identified (to be fixed).	Constrained tGAP—model for deriving intermediate scales while having the same dataset available in two scales. What makes it different from tGAP standard is the way particular feature types are weighted.
[61]	*Douglas–Peucker*	*tGAP* *Space-Scale-Cube*	Three case studies presented varying in scale and type of data used. They are described in detail.	New approach to encode tGAP structure into SSC. This solution may support true smooth zoom generalization. However, there are still some open research questions.
[64]	n/a	n/a	Model based on case—visualization of road accident data. An attempt to formalize generalization (ontology). The results are promising.	Ontological modelling to articulate the knowledge used in automatic cartographic design. The authors try to create the ontology of generalization, which produces a map.
[45]	*Douglas–Peucker*, *Douglas–Peucker–Peschier*, *Visvalingam–Whyatt*	*Generalization Expert System* (GES)	Simplification of selected features from 1:250k to 1:500k map of Canberra, Australia.	Semi-automatic spatial data mining and generalization system for polygon and polyline data. Rule-based generalization expert system interfaced with ArcGIS.
[29]	Douglas–Peucker, *Visvalingham–Whyatt*, *Gaussian line smoothing*, *Perkal's E-circle rolling*, *least-squares fitting*, *spline interpolation*, *Fourier* or *wavelet transformation*, *skeletonization*, *center of gravity*	*Constraint-based*	n/a	The authors seek an answer to the question: "can map generalization automatically produce maps at a range of scales with minimum human intervention?" It consists of a quick review of the existing generalization algorithms and operators and it discusses the potential usage and current research conducted within NMAs.
[57]	n/a	*CartACom* Topological relations: *4-intersection*, *9-intersection*, *Region Connection Calculus*	Three case studies are presented regarding spatial relations in various situations. The proposed model requires improvement in order to be useful for automatic processes.	The book chapter presents a model for spatial relations ontology. These relations can then be used in automatic processes such as generalization or on-demand mapping. They can be quantitative or predicate/binary. The authors also propose four types of relational constraints.
[68]	*Growing tide*, *rural building "squared" amalgamation*, *weighted effective area algorithm*	n/a	After releasing the alpha version of the product feedback was collected from users. The beta version includes their suggestions.	The authors present a new product developed mostly automatically—"OS VectorMap District." Some of the generalization algorithms are also mentioned here.
[46]	*Stroke-based*, mesh-based, *combined stoke-mesh*, *graph-theoretic*, *extended DBSCAN*	*Constraint-based* (soft/hard constraints)	Evaluated by professional cartographers. Only 5–10% of the objects would need to be corrected manually.	Algorithm proposed for automated road network selection (transformation from 1:10k to 1:50k. Although it was designed for Swisstopo, it should work for other NMAs.
[44]	*Least squares*, *Douglas–Peucker*, *Gaussian smoothing*, *polygon merging*, *skeletonization*, *stroke-based road selection*	*ScaleMaster* *Agent-based*	ScaleMaster 2.0 was tested on VMAP of Abéché region in Chad. Results show that this model can be used to automatically derive DCMs from a MRDB, using several generalization processes.	The article proposes an extension of the ScaleMaster model. The new version is a model that drives automatic generalization and is readable by a generalization system, while the original version only provided descriptions and left the work to the cartographer.
[47]	*Collaborative displacement method*, *snake algorithm*, *elastic beams*,	*n/a*	Two topographic data sets—urban building maps in the 1:5k and 1:25k scales. The results indicate that the proposed method is effective, but some limitations exist.	The proposed method combines aggregation, elimination and constrained reshape operators. Vector field-based displacement is adopted. If it fails, then the proposed method is used.

SVM—Support Vector Machine; NMA—National Mapping Agency; GAEL—Generalisation based on Agents and Elasticity; tGAP—topological Generalized Area Partition; VMAP—Vector Smart Map; MRDB—Multi-Resolution Database; DCMs—Digital Cartographic Models.

A detailed study by Foerster et al. [65] presented a quantitative analysis of generalization operators as indicators of the current status of automatic map generalization at NMAs in Europe. In a set of figures, the authors show the importance of operators in relation to spatial feature types most frequently appearing on maps (e.g., buildings, relief), with respect to transitions between scales. Neun, Burghardt, and Weibel [66] in their work use three different search algorithms (*hill climbing*, *simulated annealing*, *genetic deep search*) to determine the best sequence of generalization operators applied to a specific set of spatial data—urban blocks. They were evaluated in terms of processing time and the amount of conflict-reduction.

The authors of identified primary studies used various software. Some authors mentioned their own dedicated software or system [54,69–71]. In most cases, however, researchers used commercial software and, if necessary, modified it to suit their needs. S Kazemi et al. [45] proposed a knowledge-based solution build in Java-Python that is interfaced with ESRI ArcGIS for automatic generalization of thematic data (polylines and polygons). Stoter et al. [2] in their report described tests performed in years 2007–2008, where project team members used unmodified versions of commercial generalization systems (*ArcGIS*, *Axpand*, *Change/Push/Typify*, *Radius Clarity*). The main goal was to show the possibilities and limitations of existing commercial generalization software and to determine whether these systems would match the generalization criteria of specific NMAs. They analyzed four test cases but none of them was fully generalized by the unmodified systems. The Authors suggested that customization of these systems may provide acceptable results in terms of automatic generalization [2]. This had to be true as a couple of years later first fully automatic solutions began to appear [38,48,68].

3.2. Research Question 2—What Are the Existing Systems and Solutions Allowing Automatic (Tactile) Map Generation?

The review revealed that numerous solutions regarding automatic generation of maps for the blind and visually impaired exist. It identified solutions that are usually designed for the needs of NMAs regarding automatic generation of topographic maps or to allow generation of orientation and navigation tactile maps. A brief summary of our review is presented in Table 3.

Table 3. Existing systems and solutions allowing automatic (tactile) map generation (source: own work).

Article	Type of Maps	Operating Range	Tactile	Name	Study Overview
[50,71,72]	Orientation and navigation	Designed for Japan but would work everywhere (Range of OSM data)	Yes	Tactile Map Automated Creation System (TMACS)	Computer-aided platform for automatic translation of hand-drawn maps into tactile maps. In 2014 it was modified to handle OpenStreetMap data.
[73]	Topographic	Germany	No	ATKIS-Gen: Amtliches Topographisch-Kartographisches Informationssystem Generalisierung	Automatic generalization system using AGENT-Technology of 1Spatial. All the products are derived from basis DLM using model and cartographic generalization.
[48]	Orientation and navigation	City of Brno, Czech Republic	Yes	n/a	System used for partly automatic creation of a set of 1:2 500 orientation maps, ready for relief printing on microcapsule paper. Map sheets are combinable into larger areas.
[69]	Destination (navigation)	Wherever Bing Maps are available	No	Destination Maps under Map Apps (discontinued)	Fully automated system for creating destination maps that is based on principles used by mapmakers. The system simplifies selected roads, optimizes their position, scale and orientation, and adds geographic contextual information.
[74]	Tourist	Determined by the database content (e.g., 3D buildings)	No	n/a	Automatic generation of tourist maps based on an existing database, which is constantly updated (according to authors).
[75]	Topographic, Historical	Whole world (depends on map type selected)	No	Carte-a-la-carte	Existing system enabling customers to define a customized paper map (not free of charge). It is possible to include the title and a cover illustration (logo), using three kinds of maps.
[70]	Road atlas	Global	Yes	Mapy.cz	Conventional map underlays are adjusted so that they can be printed on microcapsule paper and used by blind people.
[76–78]	Orientation and navigation	Range of OSM data	Yes	Blindweb.org	Platform for automatic generation of tactile maps based on OSM. It allows creation of graphics for 3D printing (also audio-haptic overlays) and microcapsule paper.
[79]	Orientation and navigation	Range of OSM data	Yes	Tactilemaps.net	Complete end-to-end system that allows the blind and visually impaired to independently generate tactile maps. Users can either generate a 3D model or order a print.
[80,81]	Orientation and navigation	Range of OSM data	Yes	HaptOSM	The solution is a combination of specialized hardware and software based on OSM data that allows creating individual tactile maps almost entirely automatically.
[38,82]	Topographic	The Netherlands	No	n/a	Successful methodology for automatic derivation of 1:50k maps from 1:10k data.
[42]	Topographic	Catalonia, France, Germany, Switzerland, Great Britain, the U.S., the Netherlands,	No	n/a	Description of automated generalization carried out in seven chosen NMAs (maps, label placement).
[83]	Orientation and navigation	Range of MapQuest (not clearly specified)	Yes	n/a	System for automatic conversion of JPEG images into graphics that can be used in braille embossers and microcapsule paper.
[84]	Land cover	Germany	No	CLC-generator	Methodology of land-cover datasets automatic generalization from topographic data successfully implemented for conversion of Basis DLM into CORINE Land Cover.

OSM—OpenStreetMap; DLM—Digital Landscape Mode.

In March 2013 a symposium on "Generalization within NMAs" was held in Barcelona. Duchêne et al. [42] prepared a review of the state-of-the-art within NMAs regarding automatic map generalization. Based on contributions from seven interviewed NMAs and conclusions drawn after the symposium we can assume that, as of the year 2014, the selected NMAs had made significant progress. It turned out that all considered NMAs had managed to renew their data models so that they took a form of structured spatial databases, characterized by consistency between particular levels of details. Eleven out of 12 NMAs had introduced either automatic or semi-automatic generalization processes. According to the report, examples of successful implementation of fully automatic generalization existed in Ordnance Survey Great Britain where they managed to derive 1:25k Digital Cartographic Model out of a mixed-scale Digital Landscape Model (DLM), at IGN France—1:25k Digital Cartographic Model (DCM) from a 1:10k DLM, and at Kadaster Netherlands—1:50k DCM from a 1:10k DLM. Such works facilitate the shortening of update cycles of spatial databases but are still insufficient as far as the needs of modern customers are concerned.

An interesting project in the field of automatic generalization is described by Thiemann and Sester [84]. The developed program called *CLC-Generator* allows automatic generation of Corine Land Cover data that is updated every six years from the high resolution German land-cover dataset with update rate of one year. Authors present an example workflow with generalization operators and their parameters specified.

We also identified certain solutions designed to produce thematic maps. Kopf et al. [69] presented an already implemented system for creating unique destination maps. After the user has defined the destination point, the system first simplifies the geometry of roads within a predefined range, then optimizes their position, scale and orientation in a non-uniform way, and finally adds contextual geographic information to facilitate orientation. A different solution was presented in Grabler et al. [74]. It allows for automatic generation of tourist maps. These maps highlight touristic points of interest, so that they are not only useful but also good-looking. Many commercial platforms for automatic map generation can be found online. The review revealed one that is managed by IGN France [75]. Users can order personalized maps (e.g., historical maps, or orthophotomaps) in either digital or paper form. However, this type of solution does not apply any generalization but simply downloads the necessary files from a dedicated database.

We found numerous solutions dedicated to blind and visually impaired users. Many of them are automatic systems that are based on *Open Street Map* (OSM) data. One of the examples is the *Tactile Map Automated Creation System* (TMACS). First, its authors developed a computer-aided platform that was able to recognize hand-drawn images of maps and translate them into digital tactile maps [50,71]. In 2014, the system was modified to allow automatic tactile map production of any given location in the world [72]. Based on the address entered by the user, the system generates an image that can then be printed using microcapsule paper and raised to a spatial (tactile) form. *HaptOSM* is another example of a complete system. It consists of software that uses data from OSM along with additional parameters and converts them into G-Code, and hardware: a dedicated CNC-Router that embosses map data on Braille paper of writing film [80,81]. A different system based on OSM data was described in Taylor et al. [79]. Their online platform [85] is adapted to be used by visually impaired people thanks to screen-reader compatibility. The platform has two interfaces. In simple interface users are only asked to provide an address and specify the size of the map. This is enough to generate a 3D model of roadways in the area. The advanced interface provides additional options for map customization: users can add additional features such as waterways and points of interest. Users can either order a 3D model that can be then 3D printed or directly order a physical print of their map. The system can also generate physical maps, using conductive filament. They can work as interactive overlays for touchscreens to provide dynamic touch interactivity with the maps. A more extensive system, also based on OSM data, was presented in Götzelmann and Eichler [76], Götzelmann and Pavkovic [77]. In this case not only the platform [86] can be read by screen readers but also an actual map image is generated based on user requirements. To generate a map, users have to specify an address that determines the central point of the map and choose the map features to be represented on the map sorted in categories (e.g., Health, Accessibility), map zoom level and output technology. This system is capable of generating files for 3D printing (including audio-haptic overlays), printing on microcapsule paper or compatible with braille embossers. Further developments of this platform were discussed in [78]. The paper presented a solution for audio-tactile overlays working with usual smartphones or tablets that can be 3D printed using conductive materials. Special capacitive codes are used to identify particular tactile maps being placed on a touch screen and provide audio feedback to blind or visually impaired users. The system proposed by [83] is based on MapQuest and uses digital map images. It first detects texts and extracts them so that they are processed separately from graphics. Features identified in this way are then translated into a form appropriate for tactile printing and integrated in Support Vector Machine form that enables map exploration with use of a touchpad. The system performs these operations fully automatically by just providing an input file. Output files can be printed either on microcapsule paper or using braille embosser and augmented with audio descriptions.

Unfortunately, such collaborative mapping platforms as OSM are created by people who are often unexperienced "mapmakers." These data are characterized by strong heterogeneity [87], which results in inconsistencies and topological flaws that make them unreliable. Due to that, it would be best not to use such data for automatic tactile map generation. However, OSM offers impressive coverage and enables to generate maps of almost every place on Earth. Besides, due to lack of communication between NMAs, there are few examples of cooperation between countries to provide spatial data of high cartographic quality for automatic tactile map generation. However, some actually exist. Štampach and Mulíčková [48] presented a system developed by joint efforts of public institutions and academic environment in form of Python scripts for ESRI ArcGIS software that allowed them to generate a set of 1:2500 orientation and navigation maps semi-automatically. The grid of the generated map sheets covers the whole area of Brno City in Czech Republic. Individual tactile maps were prepared to be relief printed using microcapsule paper and can be combined to form larger areas. Each map follows the proposed scheme and complies with the requirements provided by the Support Centre for Students with Special Needs at Masaryk University. Another example of existing mapping solution in Czech Republic is the one described in Červenka et al. [70]. The paper described an enhancement that was prepared for the official mapping service Mapy.cz [88]. It adjusted traditional map underlays into a form that can be printed on microcapsule paper and used by blind and visually impaired people. Again, the platform was created thanks to cooperation of public and educational institutions, as well as commercial sector.

Some of the papers did not mention any specific solutions but presented planned research in the field of automatic tactile map generation. Ducasse, Macé, and Jouffrais [89] provided information about the *AcessiMap* research project, whose goal is to improve map accessibility for the visually impaired in France. The paper also mentioned other existing solutions in the field of tactile map generation such as *Touch the map!*. It enables interaction of blind users with tactile maps (e.g., retrieving names and distances using gestures). Some commercial solutions were also presented, including *HyperBraille* for creating dynamic pin-raised displays or *SpaceSence* and T*ouchOverMap*, that rely on touch sensitive surfaces without any overlays. Another project mentioned in the paper is the one that is often referred to as a pioneering project in the field of automatic tactile map generation—*Talking TMAP*. The project was initiated in 2003 and resulted in creating a web-based software tool for fast production of personalized tactile street maps of any location in the United States. They could then be downloaded and personally embossed [90].

Current trends and a summary of research status in on-demand tactile maps generation were gathered in a review article [39]. Apart from studies identified during the review, there are two other projects worth mentioning. Schwarzbach et al. in [91] proposed a solution that allows producing colorful 3D printed maps facilitating teaching geography to blind and visually impaired people. Using similar technology enables to generate 3D models from LIDAR data and orthophotomaps [92].

3.3. Research Question 3—How to Properly Design Spatial Databases for Automatic Map Generation?

The importance of creating unified geographical datasets (RQ3) for automatic (on-demand) tactile map generation was stated in Guillaume Touya et al. [39]. The solutions used in NMAs and described in the previous sections employed systems for automatic map generation that derived consecutive DLMs or DCMs from the main spatial database. The question is how to design such database? What requirements should it match? Most of the identified primary studies provided little information on this topic. This is probably because specifications of spatial databases for automatic map generation are either classified or described in formal documents rather than scientific publications. However, there are examples of important works in this field. An exhaustive research regarding vario-scale database structure was described in [93]. The main research question of this study was how to design a system dedicated for vario-scale mapping and present a working pipeline from the pre-processing steps to the final data visualization. Examples of base datasets for automatic map generalization were described in [65]. The authors mentioned Dutch *Multi-Scale Information Model Topography* (IMTOP), Danish multi-scale *GeoDB*, varying-scale *OS MasterMap* produced in Great Britain. In France, the *IGN BDTOPO* database is updated in six-months' cycles and is used to produce multi-scale vector data [75]. The authors pointed out that in many situations it is more important to have a database that is able to produce less-detailed up-to-date results, rather than very precise but out of date topographic maps. In many cases up-to-dateness may be of higher priority than cartographic rules [82]. Nevertheless, the resulting maps must comply with basic quality requirements. In Switzerland, the *Topographic Landscape Model 3D* (TLM3D) serves as the master database out of which topographic maps and other database products are derived [46]. In Poland, the basis for the national spatial data infrastructure is the 1:10k *Topographic Objects Database* (BDOT) that is used for semi-automatic derivation of the 1:250k *General Geographic Database (BDOO)*. Currently, full automation of this process is one of the main goals of Polish NMA [94]. However, as it was recently stated in [95], it is not possible to perform automatic generalization of BDOT10k, using out-of-the-box software. In the Netherlands, a decade ago the authorities wanted to develop a new large-scale topographic standard of a vario-scale database—*IMGeo*. One of the ideas proposed by Hofman [96] was to make the *IMGeo* model based on existing constraints from the *Top10NL* standard using constrained *tGAP* approach. The main focus of this work was on generalizing polygon features. The requirement for *tGAP* approach is that area partition should cover the whole map. That turned out to be a real problem as the *Top10NL* structure did not match this criterion [96]. Constrained *tGAP* approach can be used to derive intermediate scales of maps but with one limitation—a final scale dataset has to be known a priori [61].

In general, two different approaches are being used by NMAs regarding the way certain products are created out of the main DLM: "star" and "ladder." In the "star" approach every DLM or DCM is derived directly from the main database through generalization, while in the "ladder" approach the base DLM is generalized to form a lower resolution DLM or DCM, which is then generalized into an even coarser DLM or DCM [42]. According to the report by Cécile Duchêne et al. [42] the only NMA using the "star" approach is Ordnance Survey Great Britain. The rest of the NMAs use a mixed approach (e.g., [73]). Most of the NMAs (eight out of 12) decided to implement Multi-Resolution Database (MRDB) that allows maintaining links between different DLMs and DCMs.

The problem with these databases is that they are not interrelated. Globally available spatial data such as OSM are unreliable (cf. Section 3.2—RQ2), but they can be dynamically updated. Besides, some researchers suggest that solutions for on-demand generation of tactile maps should rely on the kind of spatial data that are free to use and publicly available [89].

An idea on how to use a certain database structure for storing planar spatial data was presented in Xiang, Huang, Shao and Wang [97]. The authors proposed their implementation of popular NoSQL MongoDB and evaluated it as a highly capable, rich query language choice to manage spatial data. Their main goal was to combine the strengths of both MongoDB and R-tree structure to support geodetic spatial data management and to provide queries with spatial predicates, while at the same time speeding up the query processing. This will influence the process of selecting appropriate objects for map generalization. There is a close correlation between spatial data and the constraints that determine their generalization. Stoter et al. [98] argued that they should be as formal as possible to support the generalization process and its evaluation. The same applies to databases used for automatic derivation of maps. They have to be consistent, unified with other databases, and topologically correct.

An issue that has been tackled in Boedecker [99] is the simultaneous generalization and coordination of various feature types. In order to solve this problem properly, a generic set of cartographic relations that will be preserved during generalization has to be defined. Data enrichment is one of the ways to preserve them. This should make the generalization level of different thematic features well-balanced. These cartographic relations (namely: geometric, topological, statistical and semantic) support the coordination of different map themes during generalization. A similar issue was discussed in Jaara, Duchêne, and Ruas [100]. In the real world, reference and thematic data might come from various sources. A process called thematic data migration is essential to maintain data consistency, for example while merging thematic data from different sources. The authors presented a methodology based on "relation satisfaction measure" as a good way of evaluating thematic data migration. This issue might be avoided if one unified master database existed. Even so, great caution has to be taken while using such master database. Kazemi et al. [101] argued that, during generalization, an initial decision on how much initial data should be discarded from the master database results in a more varied final dataset than the choice of certain generalization operators or algorithms. This might be an obvious statement, but it clearly shows how important it is to design a spatial database properly.

4. Discussion

We can assume from full-text analysis that most of the evaluated existing solutions in the field of automatic (tactile) map generation (RQ2), were described in primary studies from years 2014–2018. This is especially true for online platforms for tactile map generation. We were happy to see that the number of systems for automatic map generation is growing constantly. At the same time, we are concerned about the fact that many of them seem to have been discontinued. We are unsure if this is because of lack of funds or because these solutions proved to be useless in the real world outside the lab. Another problem is that even though researchers can currently communicate freely and have almost unlimited access to knowledge, collaboration between them seems scarce. Solutions produced in different countries or even different research centers are not transferred and shared. This is also true for spatial databases used for automatic generation of various cartographic products, which is even more surprising as most of the solutions developed for the blind and visually impaired are based on worldwide available data from open mapping projects such as OSM. In general, more than half of all systems identified in the chosen set of primary studies were designed for blind and visually impaired people. However, none of them deals with thematic tactile maps used in education. Most of the identified systems are designed for generating orientation and navigation maps.

Automatic map generation is an optimization issue for many NMAs. Their aim is to transform high-scale spatial databases into lower-scale topographic maps using model and cartographic generalization. The most popular challenge for NMAs is to create intermediate levels of maps based on existing spatial databases. Besides, there is an on-going discussion on whether it is better to prioritize the up-to-dateness or the quality of these databases. In a modern, dynamic world people expect to have all the information immediately, but NMAs are institutions that should take extreme care regarding quality of the data they provide. Although this might be the result of search bias, it looks like most of the work in the investigated field is currently being carried out in Europe, the U.S. and Japan.

After attempting to answer RQ1 regarding the best algorithms and models for automatic map generalization, we can conclude that this question remains open. Despite the amount of time researchers devoted to it in recent years, there are still no holistic solutions in this field. It might be interesting to note that according to some experts one does not need new models but a methodology that will allow to combine them and thus realize their full potential [59]. A confirmation of this statement can be found while analyzing algorithms used for automatic map generalization. Most of the studies used popular algorithms such as *Douglas–Peucker* or their modifications that have been known for years. Moreover, most of the identified models used a constraint-based approach. Perhaps we do not need something completely new to solve the evergreen issue of automatic generalization?

We believe that building a unified, verified and up-to-date spatial database is a good starting point. In times of Volunteered Geographic Information, when people provide their location by georeferencing photos or social media posts and cooperate in projects such as OSM to build global cartographic coverage, this "elusive dream" might become reality. Some examples of such master databases already exist (cf. Section 3.2), but this is not enough. Again, instead of building something completely new, as in the case of generalization models, one should consider adapting the existing solutions. The Open Street Map project has great potential, but it has to be formalized. In our opinion, some full-time data validators should be employed in order to ensure the right quality of the provided data.

We believe that this systematic review presents a brief overview of the current state of research in the field of automatic (tactile) map generation, and that it will provide new directions for research and development. To summarize, the review presents the current gaps in the research and issues identified during review:

1. Despite various existing generalization algorithms and models, a holistic solution that would be able to process the entire map at once does not exist;
2. There is no collaboration between researchers and NMAs dealing with this topic. Many of the working solutions were never implemented outside the country of origin;
3. The existing solutions for automatic tactile map generation are based on unmodified data. Spatial data has to be transformed into the form legible for the blind and visually impaired first;
4. There are no existing solutions for generating automatic thematic tactile map that could be used in education;
5. Despite the existence of the European Union INSPIRE Directive, the spatial databases of EU member countries are still not fully compatible.

The reviewed papers as well as the identified gaps form the basis for a research agenda regarding automatic tactile map generation. In our opinion it might be a good idea to transfer the verified and working solutions developed for automatic generation of traditional maps into the field of tactile cartography, which seems to be more reasonable than developing entirely new solutions from scratch. However, this requires developing generalization rules customized to the perceptual possibilities of the blind and using a different approach to map composition, having in mind the specific requirements of tactile maps design. As in traditional cartography, we should develop rules for updating such maps, as well as try to use already existing data, generalized to a level acceptable to blind people, in the development of new maps. It can reduce the time of developing maps for the blind and reduce their costs. While working on this, researchers should try to implement the principles of universal design. Currently a lot of effort is being put in the unification of various databases, such as in the case of European Union and thus, international cooperation between research centers and public institutions should be of high importance in future projects.

As a number of working solutions for orientation and mobility tactile maps exist, researchers should now focus on educational tactile maps. We think that so far there has been too little research in this field. This kind of map is necessary for the proper implementation of the curriculum for blind and visually impaired children. Future projects should take advantage of new production techniques, such as 3D printing, and implement the described ideas to make the maps more interactive (e.g., refreshable displays, audio feedback).

At this point we have to discuss the limitations of this review. First of all, we did not cover all the existing electronic databases but only selected ones. Analogue materials were not deeply investigated, either. Besides, the electronic databases differed from each other. They were based on various search engines that required different search queries. Nevertheless, we tried to modify them so that they would provide similar results.

This review is also prone to search bias as during keyword-based search we used those keywords that are influenced by our academic background. As a result, some studies in other disciplines might have remained undiscovered. The process of Title–Abstract–Keywords analysis is subjective and this is why this phase was conducted by two independent reviewers in order to minimize bias. To ensure that the quality of the chosen studies was high, we used quality assessment forms during full-paper screening. Studies that did not receive the required score were also excluded (504). In order to allow reproduction of this step in the future we tagged all the excluded studies in a manner described in the Review Protocol (Figure 6).

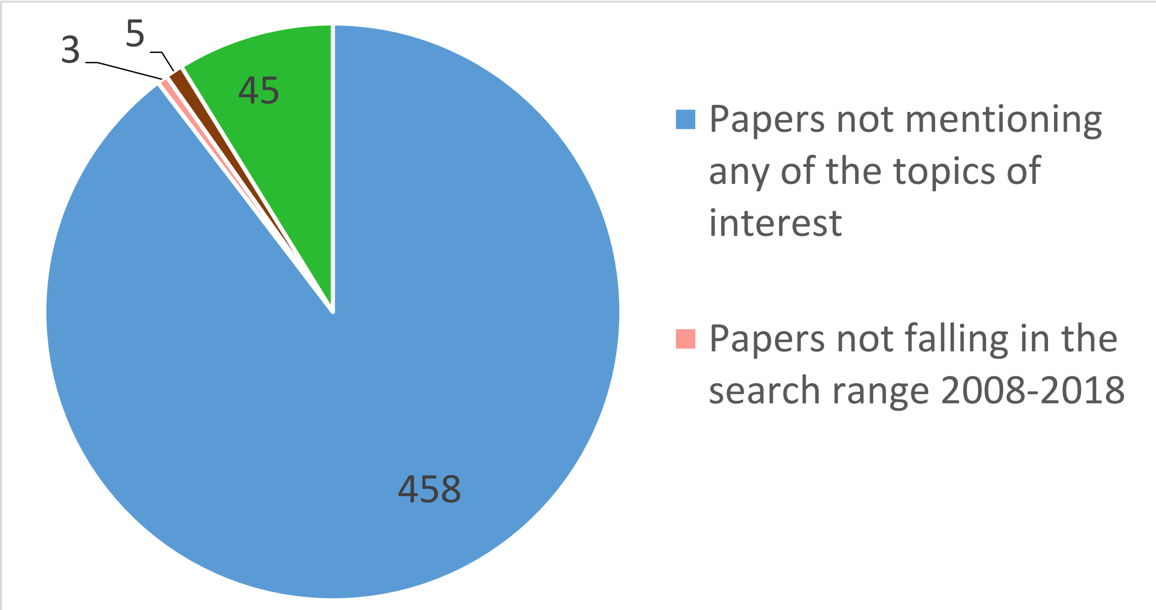

Figure 6. Reasons for the exclusion of certain papers from the review (source: own study).

The most popular reason for the exclusion of certain studies was the fact that they were unrelated to any of the research questions (458). This decision was made without full-paper screening and thus, it might be biased. Another limiting aspect was that some of the studies were written in languages that we were unfamiliar with (5). Some of the papers' metadata contained false information about the publication year. Those published before 2008 were excluded (3). We also have to mention that most of the studies' metadata was not machine-readable and, as a result, we had to conduct some of the presented analyses manually. The fact that we analyzed only the research from the last decade is another limitation. During backward reference search we also chose only studies from years 2008–2018. In fact, backward reference search was also subjective because it was based on Title–Abstract–Keywords analysis. Due to time limitations this process was conducted only on studies selected during full-paper screening (34). However, there might be some valuable research papers among the citations of the initially identified studies (566).

5. Conclusions

This article presents a systematic literature review on the research status regarding automatic (tactile) map generation, with a focus on generalization algorithms and models, existing solutions and methodology of spatial database design to serve this purpose. By using transparent workflow described in the Review Protocol, we aimed to create a review that is replicable and reproducible. To provide an exhaustive data collection we analyzed results from many heterogeneous and interdisciplinary digital libraries. Our intention was to make this review free of bias by applying different quantitative and qualitative techniques, but obviously this was impossible. All the primary studies that we analyzed are available for researchers to investigate but unfortunately often not for free and thus, out of reach of laypersons. This is where our review might turn out to be useful. Fortunately, currently there is a strong movement to make all the research accessible to the general public and hopefully one day science will be open to everyone.

We managed to answer our research questions during the review. The overview of the existing methods might be a motivation for researchers from across the globe to cooperate. The review also identified the existing research gaps and proved that there is a strong need for new research contributions in this field. This might be an inspiration for many researchers. In conclusion, much has already been said but there is still a lot to do.

Supplementary Materials: The following are available online at http://www.mdpi.com/2220-9964/8/7/293/s1, Document S1: Automatic (tactile) map generation—Review Protocol.

Author Contributions: Jakub Wabiński designed the study and identified digital sources; Jakub Wabiński and Albina Mościcka performed the primary studies screening and quality assessment; Jakub Wabiński wrote the paper and Albina Mościcka made corrections to the text.

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Semi-automatic development of thematic tactile maps

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ABSTRACT

Tactile cartography has always been a niche topic, but even among tactile cartographers, little attention has been paid to thematic tactile maps. Thematic maps are used in education and the lack of such materials makes it difficult to fulfill particular subjects' curriculums. In this research, we propose a methodology for automatic compilation of legible and cartographically sound educational thematic tactile maps that bases on the concept of anchor layers and uses unequivocal parameters for generalization operators. Using such an approach we were able to automate the most complicated parts of the procedure that deal particularly with the generalization of geospatial data. We verify the proposed methodology by preparing a sample case study 3D printed map that is later evaluated by students with visual impairments. We also evaluate a novel approach of hybrid map production that consists of both graphic and tactile content. Our results suggest that the proposed methodology can be used for fast and repeatable production of fully fledged thematic tactile maps and that it forms a significant step toward completely automatic tactile maps development in the future.

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1. Introduction

The difficulty of tactile maps development is related with lack of unequivocal guidelines, high costs, and specific requirements imposed by limited perception skills of the people with visual impairments (PVI) (Fleming, 1990; Stangl et al., 2019).

The perception limitations result from the fact that PVI read tactile maps using mainly the sense of touch, whose resolution is lower than the eye's (Papadopoulos et al., 2018). Thus, less content can be fit on a single tactile map sheet than on its classic counterpart, and this content has to be greatly simplified or, using cartographic terms, generalized. Due to its subjectivity, generalization has always been one of the most complicated problems in cartography (Stoter et al., 2010).

One may think that less cartographic content on a given tactile map sheet means that less conflicts between features occur and thus, their redaction is easier. But if we consider the perception limitations of PVI along with the same information needs, it turns out that the generalization tasks on tactile maps are even more complicated. Tactile cartographers have to put as much content as possible on a single tactile map sheet on the one hand, and to make it legible on the other (Wabiński et al., 2020). In conclusion, a tactile cartographer, just like a classic cartographer, faces the problem of map content generalization but has other challenges, such as perception differences among individuals with visual impairments; numerous production methods with varying characteristics; or the need for tactile maps to be portable, durable, and washable.

Research on traditional maps generalization has been carried out for years. This includes developing generalization algorithms (e.g. Visvalingam & Whyatt, 1990; Weiss & Weibel, 2014), resolving graphic conflicts (Harrie & Sarjakoski, 2002; Mackaness, 1994) or automating orchestration of generalization algorithms (Brassel & Weibel, 1988; Cebrykow, 2017). With regard to tactile maps, only recently have the researchers tackled the issue of their generalization, but only in the context of orientation and mobility maps (e.g. Štampach & Mulíčková, 2016; Touya et al., 2018). To the best of our knowledge, no research on thematic tactile maps generalization has been carried out, and we aim to fill this gap.

In traditional cartography, especially topographic, the map preparation procedure, including the selection of the map content and its redaction, is usually standardized and accurately described (Foerster et al., 2013). Many countries have their own technical manuals detailing what and how should be presented on topographic maps that are often automatically developed on the basis of dedicated topographic databases (e.g. Davis et al., 2019; Ordnance Survey, 2004). Now, many of the

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principles developed to automate the production of topographic maps can be implemented in the process of thematic maps development (Raposo et al., 2020).

The last decade has brought an increase in research papers considering the automatic production of tactile maps (e.g. Barvir et al., 2021; Götzelmann & Eichler, 2016) but they focus mainly on production and technological aspects. Most of the existing solutions are based on unmodified geospatial data and do not consider proper cartographic generalization, which impacts the final products' legibility and reduces repeatability of map compilation (Wabiński & Mościcka, 2019). Moreover, the issues related with tactile map compilation do not only concern generalization and production of physical copies. Numerous redaction rules affect tactile symbols design and their placement on a map sheet.

Even though some guidelines and good practices exist, they are inadequately described. Some of the possible reasons for such a state of affairs is the lack of cooperation between institutions issuing such guidelines and the excessive number of production techniques that have different limitations. Besides, the standardization is additionally complicated by the variety of sight disorders, different levels of tactile education, or even personal preferences of PVI.

All this makes tactile cartography a niche topic. National mapping agencies usually develop tactile maps production standards only for their own needs, without translation to other languages. In many countries, no official documents exist. In some cases, only collections of unofficial good practices provided by tactile map makers are available (e.g. Bris, 2001; Więckowska et al., 2012). Thus, tactile maps development is a difficult and time-consuming process. Their production is expensive, hard to systematize and standardize.

Fortunately, emerging production methods that allow fast prototyping, such as 3D printing, allow researchers in this field to verify new design approaches in a more efficient way (e.g. Gual et al., 2014; Holloway et al., 2019; Voženílek & Vondráková, 2015). Their application, along with the research on, at least partial, tactile maps development automation, creates possible conditions for their faster, cheaper, controllable, and repetitive production.

Therefore, our research aim was **to develop a methodology for automatic compilation of legible and cartographically sound thematic tactile maps used in educational environments**. Many of the existing solutions of automatic tactile map generation usually base on unmodified data and focus on orientation and mobility maps, whereas thematic maps are often neglected (Perkins, 2002; Wabiński & Mościcka, 2019). Thematic maps are used in schools as educational materials. The lack of such maps complicates the fulfillment of subjects' curriculums. Our research aims at filling this gap and broadening the access to educational thematic tactile maps for both tactile and visual perception among students with visual impairments.

Bearing in mind our previous research in this area on information value of tactile maps (Wabiński et al., 2020), our proprietary design solutions increasing tactile maps legibility and/or information value (Wabiński, Śmiechowska-Petrovskij, & Mościcka, 2022), as well as our literature analysis in the field of automatic map development (Wabiński & Mościcka, 2019), we have posed the following research questions:

RQ1. What procedures and rules allow automation and repeatability of the thematic tactile map development process?

RQ2. Which steps in this process can be fully automated?

Finding answers to these research questions will largely fill the existing research gap by ensuring acceleration and repeatability of thematic tactile maps creation process, significantly contributing to the automation of tactile maps development and as a result, increasing their accessibility by PVI.

2. Methodology

2.1. Map development procedure

The proposed methodology is designed for semi-automatic development of small-scale tactile thematic maps by generalizing and adapting the open geospatial data. We assumed that defining the parameters of tactile symbols design and map content generalization, as well as a precise description of the procedure for the development of a selected type of tactile maps, will enable the automation of their creation and reproduction. This process greatly depends on the production method chosen but will make the whole process faster, cheaper and repetitive.

The main idea of our methodology is to first prepare a basemap that would remain unchanged across every map within a set, using so-called *anchor layers*, and then to adapt thematic content so that it fits to the basemap. We assume that all the maps within an atlas or a map set are in the same scale. If the scale is to be altered, one has to prepare separate generalization strategies for every basemap planned, by modifying the numerical parameters, considering the altered reference scale and, possibly, newly generated graphic conflicts.

The starting point for the presented methodology was a concept of the global master plan proposed by Ruas and Plazanet (1997) that determines a general schedule of generalization actions to be taken that, in principle, remains unchanged regardless of the map's target group or production method selected. The parameters of the global master plan should be tweaked and adapted depending on the map to be developed in the future generalization tasks, e.g. when mapping different phenomena. The following subsections describe the consecutive steps that form the master plan:

(1) anchor layers selection and their hierarchization,
(2) generalization constraints determination,
(3) basemap development,
(4) thematic content selection and its generalization,
(5) symbolization and labeling.

The methodology proposed can be used along with various map production techniques but for our case study map we decided to use 3D printing (Figure 1).

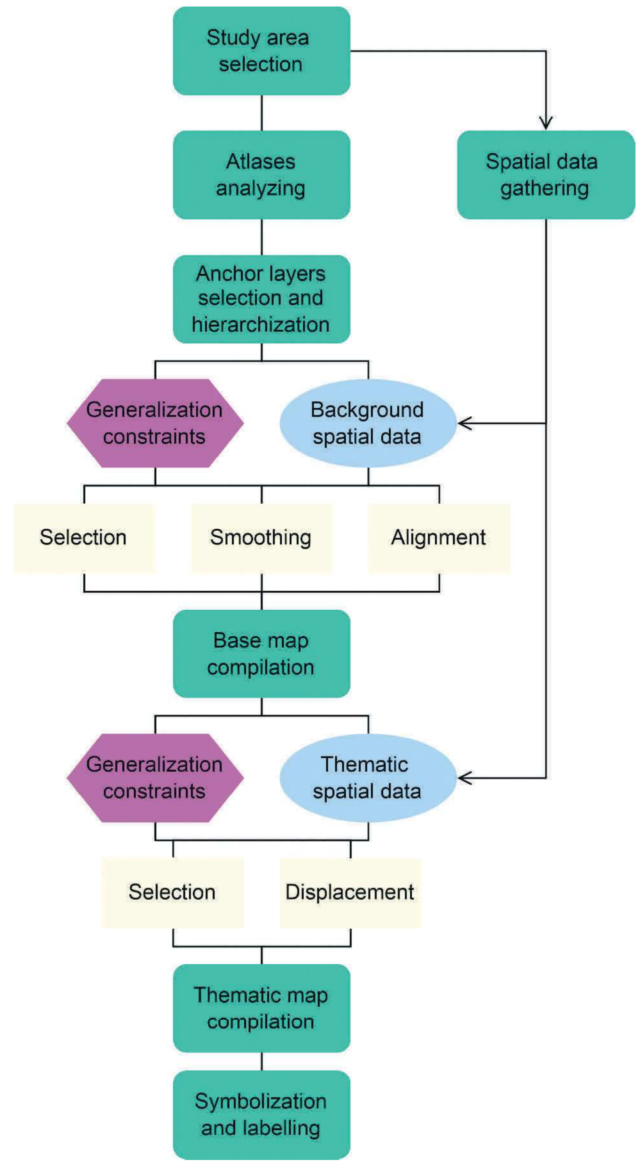


Figure 1. The methodology applied on a case study map. In light yellow are the fully automatic processes.

2.1.1. Anchor layers selection and their hierarchization

First, one has to define the area to be mapped and select the data that would form anchor layers. These layers are meant to form a basemap and will be common for every map in a given thematic atlas or map series. Unlike thematic layers that present the map's main topic, the base layers help the map reader to geographically contextualize the thematic content. In other words, they anchor the thematic layers into a representation of space that is known by the map reader.

Anchor layers, once generalized to a form legible by PVI, remain unchanged across different thematic maps of the same area and scale. Any additional thematic content has to fit these anchor layers. Such an approach facilitates the map reading process because a reader, once familiarizes himself/herself with the basemap, can focus only on the thematic content of the remaining maps in an atlas or map series.

The concept of anchors was introduced in spatial cognition to describe the landmarks that people use to anchor their mental representation of space (Couclelis et al., 1987). On a mental map, the places around one's home are usually anchored by the location of this home. A similar concept is used in multi-scale cartography to describe the landmarks (not necessarily layers) that connect two maps at different scales (Touya et al., 2021).

In our methodology, only one scale is considered, but a similar vocabulary can be used. We define the important background layers as *anchor layers*. They are important in the context of a tactile atlas (or map series) because they appear on each of its maps facilitating perception of the thematic content.

The anchor layers should be generalized first but without a decent level of displacement and distortion to continue organizing and anchoring the remaining layers (Duchêne, 2014; Ruas & Plazanet, 1997).

One can arbitrarily choose the features forming anchor layers. Hydrographic features (oceans, seas, and rivers) or national borders are recommended as a primary choice (Grygorenko, 1970), but due to cultural specificity of maps in different parts of the world (Holloway et al., 2019), the selection of additional anchor layers might be problematic. In such cases, a more systematic approach could be used. One solution is to perform an analysis of the existing thematic atlases of the given study area, to see which layers are the most common, and use them as anchor layers.

After deciding upon the data to form the anchor layers, their hierarchy for generalization operations has to be set. As the stage of basemap development includes generalization of geospatial data, and as these data could have different geographical accuracy, some geometrical conflicts might occur. Thus, the hierarchy of anchor layers has to be set.

According to Grygorenko (1970), the shorelines and rivers form a line between the two geographical environments: land and water. These features form a canvas of a map, based on which other features are mapped. For this reason, the geographical location and the level of detail of hydrographic features mapped must be precise. In the process of map development, such features are usually mapped first. All other anchor layers (e.g. national borders or cities) should then align with hydrography.

After the anchor layers and their hierarchy are determined, it is necessary to gather the geospatial data required for tactile map compilation – for both basemap and thematic content.

2.1.2. Generalization constraints determination

In our methodology, we considered different types of generalization constraints (as referred in Ruas & Plazanet, 1997): legibility (e.g. minimum point symbol size), spatial (e.g. maximum displacement of features), shape (e.g. alignment of two close line symbols), and semantic (e.g. the percentage of features to be preserved in the final dataset).

Considering the characteristics of tactile cartography, we have also followed the hierarchy of the constraint types in our methodology. In the case of tactile maps, legibility is the most important factor. In tactile cartography, it is sometimes even recommended to resign from adhering to the mathematical foundations of cartography in favor of increased legibility.

The spatial constraints maintain real-world topological relations on tactile maps, but at the same time, the maximum allowed displacements of features in tactile cartography are higher than in classic cartography. Finally, shape and semantic constraints should also be considered, but only to ensure adequate legibility of a tactile map.

Cartographic conflicts are configurations of the map symbols that either contravene the rules for a proper perception of the symbols or the design guidelines of the map (Mackaness, 1994; Touya, 2012). The tactile maps have three main sources of cartographic conflicts: the fact that tactile perception is less sharp than the visual perception (Klatzky & Lederman, 2003; Yanoff et al., 2009), the fact that they are thematic maps, with thematic layers on top of background layers (Duchêne, 2014), and the use of data from different heterogeneous sources. Table 1 shows the different types of conflicts that we face designing thematic tactile maps, following the concept of anchor layers.

The amount and nature of the conflicts occurring on a particular map depend mainly on the map's topic and the data used but also on the generalization parameters applied. Enumeration of all possible parameters is not within the scope of this manuscript.

Although no holistic solution has yet been developed for automatic tactile map generation (Wabiński & Mościcka, 2019), a number of more or less official guidelines exist that facilitate determination of generalization constraints (e.g. Eriksson et al., 2003; The N.S. W. Tactual and Bold Print Mapping Committee, 2006; Więckowska et al., 2012).

2.1.3. Basemap development

Currently, we can benefit from an abundance of geospatial data available online. The problem is that these data can be messy. Another issue is that such raw geospatial data are not legible by PVI, so a decent level of generalization and adaptation is required.

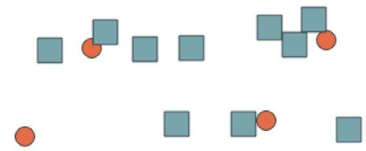
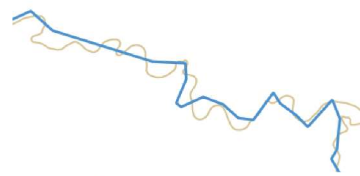
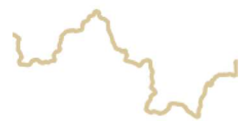
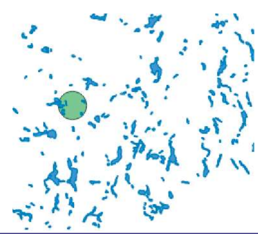
To filter the original data and maintain only the most meaningful features to form an uncluttered basemap, various selection operations can be used. Selection by attributes and by location can be easily parametrized without considering particular generalization constraints.

Taking a systematic and numerical approach for the description of the generalization process allows its automation, but requires the determination of generalization constraints. Therefore, we defined the exact values for generalization constraints, such as maximum width of a line symbol or the optimal distance between two similar tactile symbols, to parametrize the whole process. These values base on the aforementioned existing guidelines for tactile maps development and our past experience in this field (Wabiński, Mościcka, & Touya, 2022). Such constraints allow obtaining repeatable results when working with different study areas and/or data. Our methodology involves a set of operations that can be carried out automatically after defining the generalization parameters.

To prevent linear features from being too detailed in the final map, line smoothing can be applied. Such an operation is of great importance in the case of tactile maps, as detailed polylines feel very unpleasant while touched.

The smoothing algorithm that we recommend to use is Polynomial Approximation with Exponential Kernel (PAEK). It uses a parametric continuous averaging technique to calculate the smoothed shape of the original linear symbol (Farin, 2002).

Table 1. Possible conflicts on thematic tactile maps.

Description of the conflict	Source of the conflict	Example illustration
Existing relation: two types of point symbols overlap (Duchêne, 2014)	Thematic map and haptic perception	
Existing relation: point symbols overlap with line symbols (Duchêne, 2014)	Haptic perception	
Expected relation: two line symbols should overlap (Duchêne, 2014)	Heterogeneous data	
Too detailed line features	Haptic perception	
Too high density of features	Haptic perception	

While generalizing the geospatial data, one must also consider topological relations that should be transferred from the real-world features into the designed map. For this reason, our methodology involves a number of alignments.

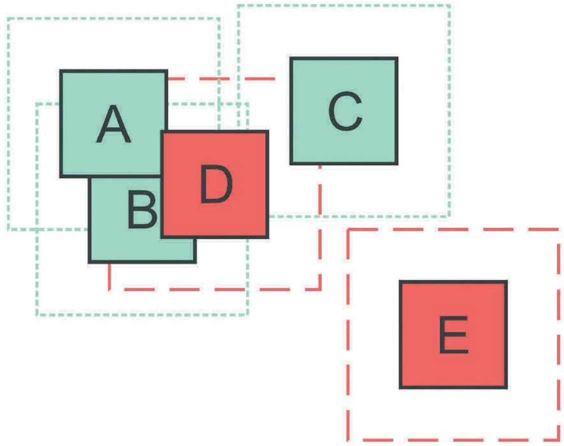
Since there are no explicit rules about the maximum distortions that can occur on tactile maps compared to the real-world features, the thresholds for the displacements can be selected arbitrarily to fulfill the original topological relations between features and maintain map's legibility.

2.1.4. Thematic content selection and its generalization

Having a basemap that will remain unchanged across various maps in an atlas or map series, one can now add the thematic content. The main rule here is that all the additional thematic layers have to fit to the basemap content and not vice versa.

To fit thematic content to a basemap, additional generalization constraints are necessary. Apart from the constraints that govern the placement of features on a map (similar to those applied in the basemap development), one has to consider others that derive from the tactual perception limitations. For example, the maximum number of textures to be placed on a single tactile map is limited to 4–6 (Jesús Villalpando Esparza, 2014; Červenka et al., 2013), whereas the total number of distinct symbols should be limited to 10–15 (Rowell & Ungar, 2003).

Similar to the hierarchization of anchor layers, the priorities must also be set for the thematic layers. Two approaches can be taken here. The first is to consider the importance of particular thematic layers for the map's comprehension and informativeness. The second is to begin with the layers, whose generalization would be the most laborious, considering, for example, their geometries – line and area symbols should be fit first.



feature	occurences	conflicts	proximity
A	3	2	2
B	3	2	2
C	3	0	1
D	2	2	3
E	2	0	0

Figure 2. Feature priorities for generalization. Dashed lines represent proximity buffers and color represents feature type, e.g. red is coal and green is crude oil.

The Python algorithm specifically written for this study adds additional parameters that determine the importance of particular thematic features to eliminate less important ones by applying a selection operator. The algorithm first counts the number of resources of a specific type (occurrences). Those with the least number of occurrences within a dataset (i.e. rare mineral resources) will be given higher priority during generalization – the algorithm will try to maintain them in the generalized dataset.

Then, for each feature in the dataset, in an iterative process, the number of conflicting features (conflicts) is counted. Those with the highest number of conflicting features will be given higher priority. Since the algorithm considers graphic conflicts, it is possible to set the desired dimensions of features to be considered including their size and the minimum horizontal distances between them (Figure 2).

Lastly, even further proximity of every feature is considered – a number of features falling within a specified buffer around a given feature are counted (proximity). The lower the value of this attribute, the higher the priority of the feature in the generalization process – the algorithm will try to maintain more isolated features in the generalized dataset.

The algorithm then uses these values to eliminate conflicting features based on the priorities assigned. It also considers the input parameters – the reference scale, symbol dimensions, and the minimum horizontal distances between them.

The approach that we describe here for thematic content generalization was designed specifically for point geometry but could be easily modified to work with other geometry types if considered along with the other possible conflicts. For example, if the thematic content would be in the form of area symbols, additional steps of lines smoothing (similar to those described for basemap development) could be applied prior to the elimination of the irrelevant features.

Because this algorithm only considers conflicts between features within the thematic layer, we also had to handle conflicts with features forming a basemap. The resulting base and thematic features were exported and further processed in the CartAGen platform – an open-source platform designed for research in map generalization (Touya et al., 2019).

We used a displacement algorithm available on the platform, called random iterative displacement. It is based on an iterative process that tries to minimize the total number of symbol overlaps in the dataset. At a given iteration, the symbol that overlaps most of its neighbors is chosen and randomly displaced. If the overlap is the same or worse, the displacement is backtracked; else the displacement is validated and another symbol is chosen and displaced (Figure 3).

2.1.5. Symbolization and labeling

Although the final symbolization is applied at the end of the map development process, one has to take into account all the related constraints in advance. First, the minimum dimensions of symbols should be used as a parameter in the generalization step and the final symbology has to comply with the previously used constraints.

At this point also the maximum number of distinct symbols on a single tactile map sheet should be considered. Moreover, one has to decide, whether the final map would consist of only the tactile content suitable for tactile exploration, or also highly contrasting graphic

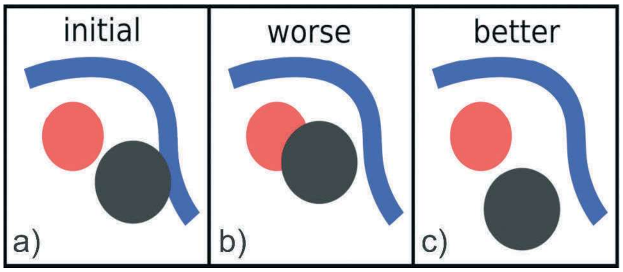


Figure 3. Principles of the random iterative displacement algorithm. When the displacement worsens the symbol overlaps b), compared to the initial state a), it is backtracked. When it gets better c), it is validated and another symbol is chosen and displaced.

elements for those with residual vision. These two content types could be merged to form a hybrid map. When symbolizing and labeling, they should be considered separately due to the differences between visual and tactual perception.

Just like in classic cartography, when designing symbols for PVI, the most important rule to follow is that the symbols should resemble the real-world objects they represent on a map. The problem is that complicated pictorial symbols are only meaningful to those adventitiously blind and partially sighted (Wiedel & Groves, 1969). Besides, tactile symbols should be as simple as possible but also ought to be differentiated along as many tactual dimensions as possible (Nolan & Morris, 1971).

A number of works describe recommended sets of legible symbols that can be used on tactile maps (e.g. BANA and the CBA, 2010; James, 1975; Nolan & Morris, 1971). The general rule of thumb is that the simpler the geometries and the bigger the distances between symbols, the more legible the map is. Unfortunately, at the same time, many of PVI prefer small portable maps (Rowell & Ungar, 2003), leaving tactile cartographers with limited space.

The final design step is to label the mapped features and prepare the final layout. When preparing a hybrid map, two types of labels have to be placed. Based on the guidelines and good practices in terms of inscriptions design (e.g. Edman, 1992; ISO, 2013), black print labels for readers with residual vision should use regular 14–18 pt sans-serif fonts to represent full names of the features described.

Because braille labels take much more space than the regular ones, abbreviations are commonly used for describing features using braille – usually 2–3 cell codes. Braille labels should follow particular standards in terms of elements' dimensions, e.g. Marburg Medium (Więckowska et al., 2012).

When preparing tactile maps layouts, the rules are similar to those in classic cartography. Map miscellanea should be grouped together, usually in the top-left corner. A legend should be separated from the map sheet using solid thick lines, and it should explain all the abbreviations used on a map (ISO, 2016; Wiedel & Groves, 1969).

2.1.6. Map printing and its evaluation

The production method should be selected prior to the map development process as the map preparation guidelines might refer to particular methods that have their unique requirements, which greatly affects the parameters to be used in the generalization process.

The map production process might include, for example, proper coloring, scaling, extrusion to a 3D model, matrix preparation, and so on. Moreover, many production methods require post-processing to assure durability as well as proper physical and chemical properties of the final products.

Many of the solutions developed for people with special needs, including tactile maps, are only tested in laboratories and lack feedback from the end users (Albouys-Perrois et al., 2018; Elli et al., 2014). For this reason, it is necessary to perform product evaluation that would allow tweaking the proposed solutions and verify its utility in the real-world conditions. Even though this paper focuses on the conceptual work, we have decided to perform a non-systematic evaluation of our final product among students from the secondary school for children with visual impairments.

2.2. Case study map

To verify the proposed methodology, we decided to prepare a case study map. The map's topic is the occurrences of mineral resources in Poland. Considering the map's geographic extent and the requirements related with the suggested tactile maps formats (Bentzen, 1980; Edman, 1992), we decided to prepare a 3D printed map in 1:2,000,000 scale. This value then served as a reference scale in the generalization process.

Because we wanted the final physical map to be accessible to both tactual and visual perception, every feature on the case study map is presented in two ways: in graphic and tactile form. Thus, the map consists of two layers: a colored, flat underprint printed on regular paper (graphic map) and a transparent 3D tactile overprint prepared using resin 3D printing (tactile map).

2.2.1. Atlas analyses

In order to appropriately select the layers forming a basemap, we have decided to follow the suggested systematic approach of analyzing the existing geographic atlases. We analyzed two atlases. Both comply with the curriculum of geography for Polish primary schools. The first of them was the geographical atlas used in Polish secondary schools (Cacopulos et al., 2020). Even though the atlas consists of maps of the whole world, we have only considered maps representing Poland.

The second was the tactile atlas for children with visual impairments (GUGiK, & PZN, 2004), widely used in special schools in Poland. In this atlas only maps of Poland are published.

2.2.2. Hierarchization of the anchor layers

In our case study map, we have given hydrography the highest priority. Next, we mapped the country borders since many of them align with natural borders like rivers. Lastly, cities were aligned with the hydrography and borders layers to maintain topological relations with these features.

Once the anchor layers are drawn, they cannot be altered. For this reason, any thematic content added had to adapt (by applying appropriate generalization and redaction) to the basemap. In this case, we mapped places, where particular mineral resources are being extracted in the form of point symbols representing different types of the resources. By maintaining the layers on basemaps unchanged when adding the thematic content, we obtained a universal reference for every future map in an atlas or map series.

2.2.3. Generalization procedure

In the process of map generalization and redaction, we wanted to consider the possible conflicts described in section 2.1.2. Smoothing and alignment operations required us to follow particular numerical parameters based on the existing tactile maps design guidelines. Our methodology assumes these operations to be carried out automatically, so we needed to extract specific generalization parameters from the literature (Table 2). These parameters were implemented and described in the Results section along with the selected reference scale.

Table 3 presents other parameters we followed that are not directly related with generalization but impact the final map's legibility.

In our case study map, the mineral resource layer (thematic content) contains only one additional attribute, apart from the spatial ones. It determines the type of mineral resource, e.g. coal.

After the selection procedure using the proprietary Python algorithm, the displacement procedure has been carried out in CartAGen. This step only displaced the features without affecting the numbers and shapes of the features with one exception – the enhancement of the Hel Peninsula.

The Hel Peninsula is a very narrow strip of land in northern Poland that is greatly enlarged on maps due to its importance in orientation. The vertices forming its geometry have been moved away using the least squares algorithm, with a principle similar to the embankment distortion (Touya & Lokhat, 2021) to enlarge it on the final map (Figure 4).

For the features displacement in CartAGen, the following assumptions were made. Rivers were symbolized as 0.8 mm thick solid lines, whereas borders were symbolized as dotted lines (2 mm dot with 2 mm gap), to which inland seawater (solid area symbol) and cities (5 × 5 mm circles) were aligned.

Since the physical copy of our case study map would have height differentiation of symbols applied, the minimum horizontal distances between particular symbols were set to 2 mm. All the thematic features, whose geometry was set to 5 × 5 mm squares for the purpose of the proprietary Python algorithm, were then displaced considering the parameters given above.

Table 3. Design parameters implemented in our case study map.

Parameter	Reference	Value
Optimal symbol height	(ISO, 2019)	0.3–1.5 mm
Optimal point symbol size	(The N.S.W. Tactual and Bold Print Mapping Committee, 2006)	4–6 mm
Optimal line symbol width	(Wiedel & Groves, 1969)	0.5–0.8 mm

Table 2. Generalization parameters implemented in our case study map.

Parameter	Reference	Value
Minimum distance between symbols	(Wabiński, Śmiechowska-Petrovskij, et al., 2022)	1 mm
Minimum dimensions of area symbol	(Heath, 1958)	0.5 in^2
Minimum line symbol length	(Edman, 1992; Regis & Nogueira, 2013)	13 mm

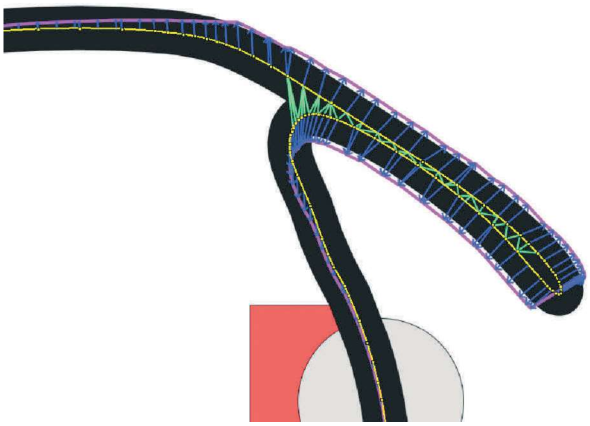


Figure 4. Displacement of lines forming the Hel Peninsula for its enhancement. The original geometry is marked in yellow, the generalized one in magenta.

2.2.4. Data used

To develop our case study map, we needed geospatial data representing rivers, cities, water reservoirs, and borders that would form a basemap and a point thematic layer representing mineral resources (Table 4).

In case of country borders, we obtained the Polish national border data from the open-source dataset but had to vectorize borders of the neighboring countries on a georeferenced raster map. The input data is presented on the map in Figure 5.

3. Results

3.1. Anchor layers selection – atlases analyses

In the first analyzed atlas (Cacopulos et al., 2020), there were four layers that appeared on each of the 46 analyzed maps: cities (point symbols and inscriptions), rivers (line symbols and inscriptions), border of Poland (line symbol), and main lakes (area symbols). Some other features appeared on almost every of the analyzed maps: borders of the neighboring countries (line symbols and inscriptions) and the Baltic Sea (area symbol and inscription).

Table 4. Data sources for the case study map.

Layer name	Data source
Country borders	• National Register of Boundaries of Poland (Państwowy Rejestr Granic) (Head Office of Geodesy and Cartography, 2022b) • Manual vectorization on georeferenced raster (1:5M)
Cities	• World Cities Esri Data and Maps (Esri, 2022)
Rivers	• Natural earth Rivers dataset (1:10M) (Natural Earth, 2022)
Water reservoirs	• Database of General Geographic Objects (Head Office of Geodesy and Cartography, 2022a)
Thematic (mineral resources)	• Manual vectorization on georeferenced raster (1:5M)

In the second atlas (GUGiK, & PZN, 2004), some features appear on every map: five main cities (point symbols and inscriptions), the Vistula river (line symbol), border of Poland (line symbol), and the Baltic Sea (area symbol and inscription). On maps in a bigger scale (1:2,500,000), additional features are presented: four cities (point symbols and inscriptions) and six rivers (line symbols and inscriptions).

Based on this analysis, we had selected the layers that formed a basemap for our case study: *main rivers*, *major cities*, *inland seawater*, *borders of Poland*, and *neighboring countries*. In the first iteration, we also included major lakes, but they introduced unnecessary clutter and we decided not to map them.

3.2. Map development process

3.2.1. Generalization procedure

Knowing the final map scale, we were able to calculate the exact numerical values of the generalization parameters to be used in our map development process. The procedure described below has been carried out in ArcGIS software, using the Model Builder module for automatic generation of the basemap.

For the generalization of water reservoirs, we have used the selection by attributes to select only the inland seawater out of the entire dataset. We then applied the area feature smoothing using PAEK with a 20 km threshold set.

In the case of rivers layer, we have first selected the rivers longer than 100 km that flow through Poland by using attribute and location queries, respectively. Next, we applied PAEK smoothing with a 20 km threshold. The rivers were then aligned (5 km threshold) to the inland seawater features to comply with the real-world topological relations.

For cities layer, we have first selected the cities that could be presented on each of the maps in a designed atlas (those in Poland with population over 200,000) and later enhanced this group by those important in the context of our case study map's topic – those that are within a distance of 20 km from the features in the original thematic content dataset (mineral resources). Finally, the cities were aligned with rivers to maintain topological relations (10 km threshold).

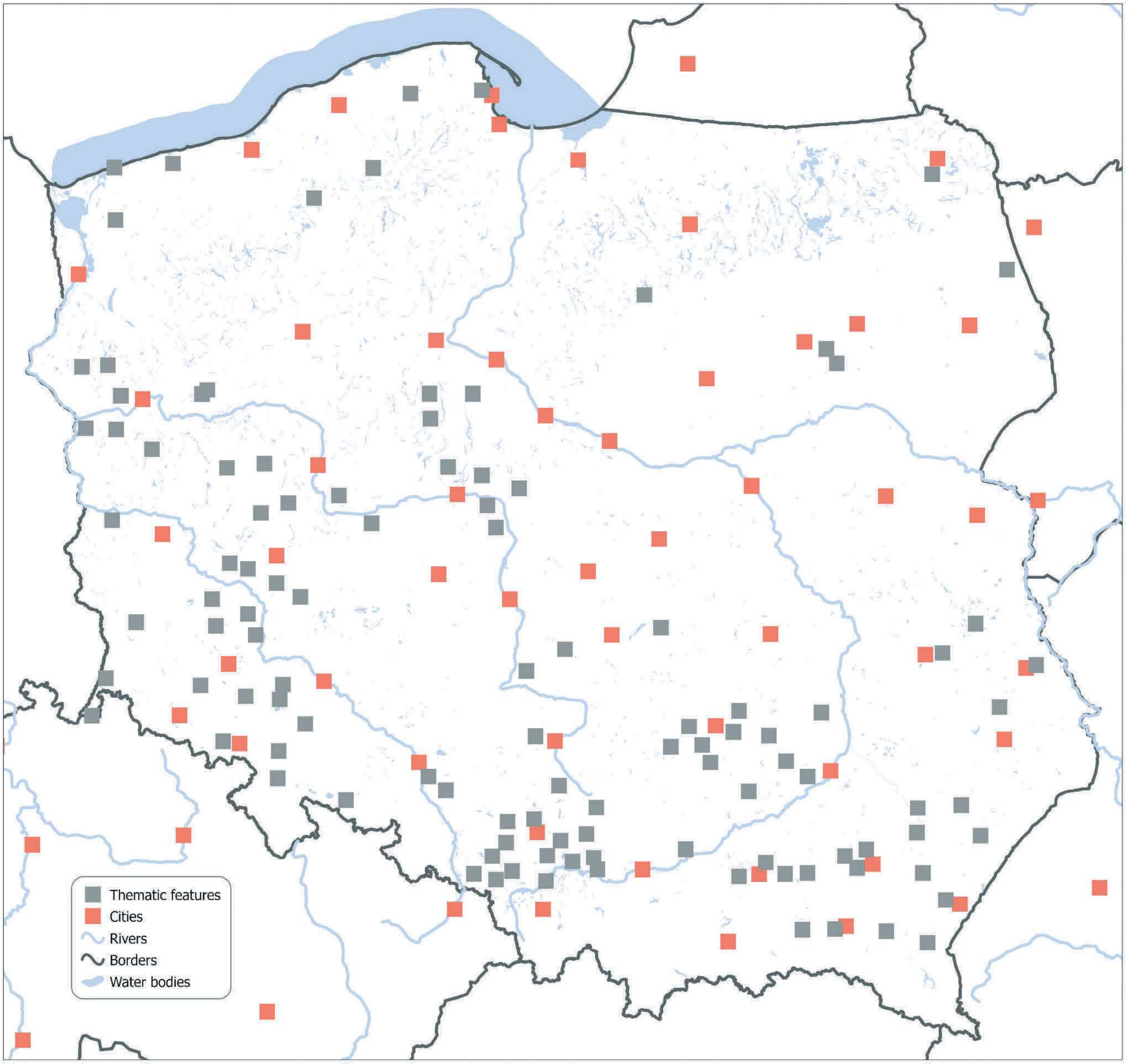


Figure 5. The non-generalized, original data on a map.

Next, the thematic content was generalized and later fitted to the basemap. The original thematic class consisted of 111 point features. After running the algorithm, 79 features remained (Figure 6).

The data were then exported to CartAGen for the additional generalization steps described in the methodology section and finally imported back to ArcGIS for the purpose of symbolization and labeling (Figure 7).

3.2.2. Symbolization and labeling

Symbology was applied to the generalized data. The data were then labeled using the Maplex Label Engine. The fact that we decided our case study map to be a hybrid map, containing both graphic and tactile content, greatly affected two feature types on it.

First, the dimensions of inland seawater features, meant to be symbolized as area symbols, turned out to be too small for tactile perception. Thus, these features are presented as area symbols on the graphic map but take the form of a raised outline representing shorelines of these features on the tactile map. All the other symbols were prepared in accordance with the existing guidelines and good practices and base on one of the existing tactile maps presenting the same phenomena (Olczyk, 2022).

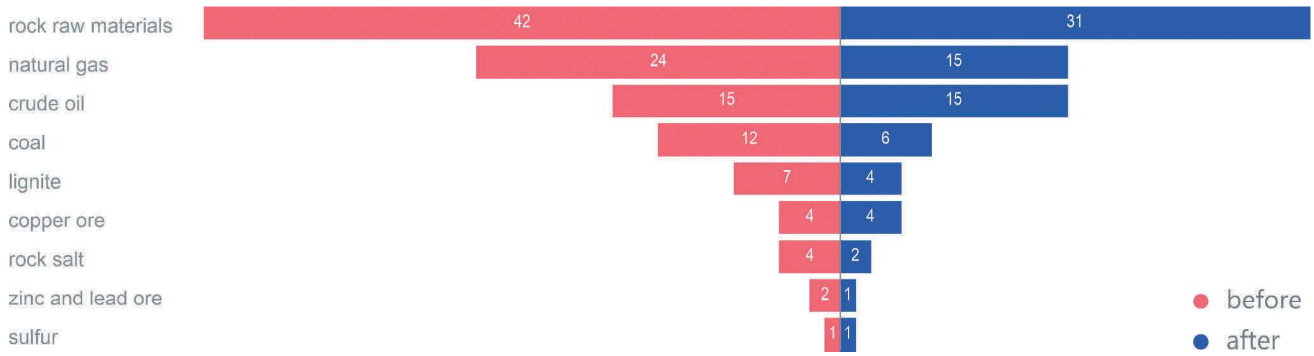


Figure 6. Count of features in the thematic layer before and after the generalization process.

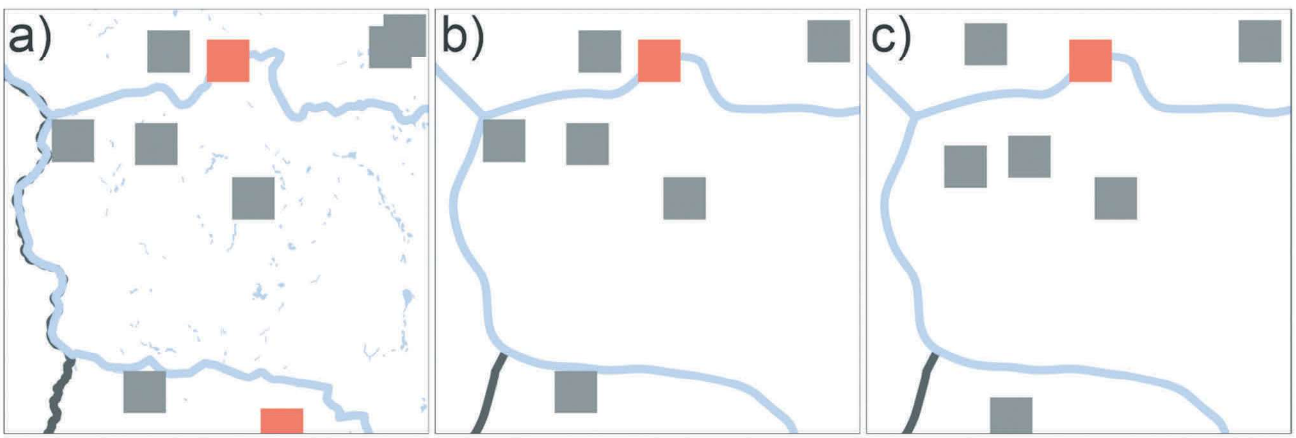


Figure 7. The effect of consecutive generalization steps shown on a map fragment - a) original data; b) data after selection, smoothing and alignment carried out automatically in ArcGIS; c) final data with additional selection and displacement applied in CartAGen.

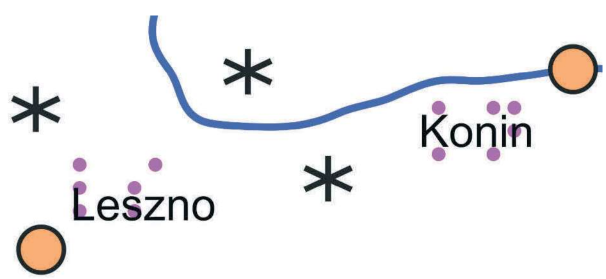


Figure 8. Two types of labels overlap for space saving. Black print labels contain full names, whereas braille inscriptions take the form of 2-cell abbreviations.

Second, the map has two label types for each labeled feature: large black print Latin labels on the graphic map and raised braille dots on the tactile map. Because the tactile overprint is transparent, it was possible to overlay the two discussed label types (Figure 8).

Labels are used on the map to describe cities and neighboring countries. Black print labels use regular 14 pt Arial font to represent full names of the features described.

For tactile labels, 2-cells braille abbreviations were used to describe cities and the neighboring countries (full names were used wherever possible). All of the abbreviations are described in the legend. Braille labels were prepared using 24 pt regular RNIB Braille font (Royal National Institute of Blind People, 2022), whose dimensions comply with the Marburg Medium Braille Font Standard. A map automatically generated in ArcGIS with symbology applied is presented in Figure 9.

The final graphic map variant consists of five layers: rivers, inland seawater, borders, cities, and mineral resources. On the tactile map, we have introduced an additional symbol – shoreline, to represent outlines of the inland seawater features. The same symbol represents the border between countries and the Baltic Sea to eliminate ambiguity related with the actual administrative borders of countries that run 12 nautical miles into the sea. On the graphic map, we have obtained a similar result by eliminating the border symbol part along the Baltic Sea shoreline (Figure 10).

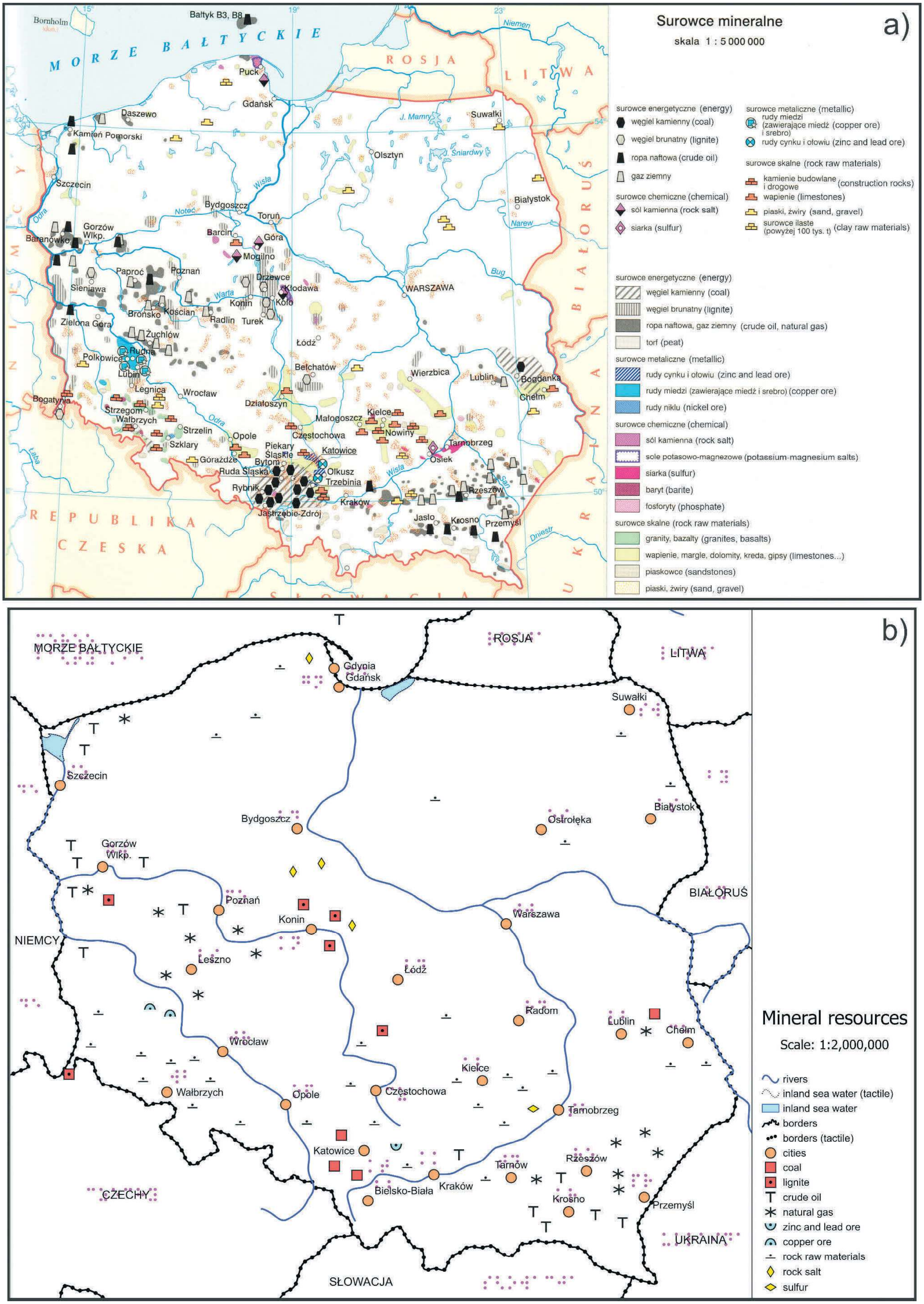


Figure 9. The comparison of map from a) theclassic atlas (Cacopulos et al., 2019) and b) the final symbolized map with all the content in graphic form.

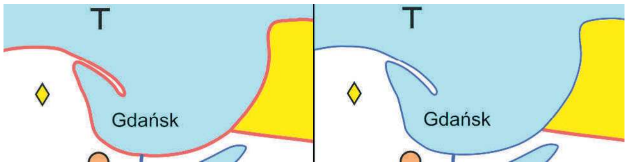


Figure 10. Modification of the border symbol along the shoreline to eliminate ambiguity.

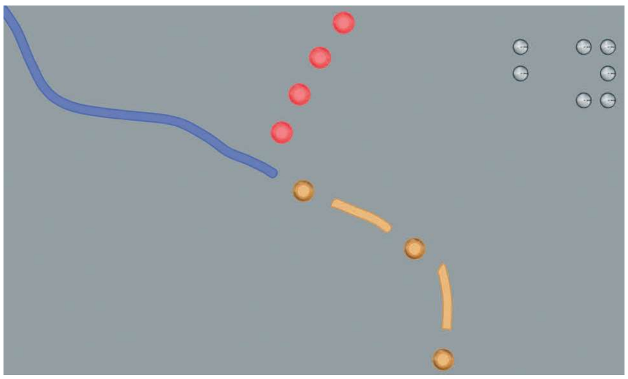


Figure 11. The additional line symbol of border on river on tactile map variant. River is blue, border is red and border on river is brown.

The mineral resources extracted in Poland have been grouped into nine types. This results in 1 area, 2 lines, and 10 point symbol types on the graphic map, and 4 lines and 10 point symbol types on the tactile map. The extra line symbol type is a result of a slightly modified representation of borders on rivers on a tactile map (Figure 11).

Finally, we generated the map's title, legend, and linear scale according to the guidelines (Edman, 1992).

3.2.3. Preparation for printing

This section briefly describes the procedure of the minor manual edits that we carried out as well as the transformation of the flat vector map into a tactile model suitable for 3D printing.

The automatically generated map has been imported into Corel software. Although our automatic approach has left us with acceptable results, we decided to perform some final attunements manually to improve map's legibility. First, we eliminated from the map one of the cities (Gdynia) that is usually not represented on small-scale maps of Poland due to its proximity to another major city – Gdańsk. We also deleted two rivers introducing unwanted clutter that usually do not appear on such maps: Neman and Mukhavets. Next, we had to displace some of the labels that the Maplex Engine failed to properly arrange. Finally, we applied colors to the polygons representing neighboring countries to increase the contrast of the graphic map (Figure 12).

The flat vector map has been uploaded into the 3D modeling software and raised to a 3D form according to the previously verified methodology (Wabiński, 2017).

To increase the map's legibility, particular symbols have been raised to different heights based on the recommendations (ISO, 2019). Thus, the shoreline symbol has been raised to 0.3 mm, rivers and borders to 0.9 mm, all the point symbols to 1.5 mm, and braille dots to 0.7 mm.

Next, we added the orientation element in the form of a convex triangle in the top-right corner of the map sheet and prepared the tactile variant of the map legend as well as the list of all abbreviations used on the map as separate geometries.

The map sheet and legend were then exported as a 3D mesh and further processed in ChituBox slicing software. The tactile overprint map itself and the legend were printed using stereolithography 3D printing with transparent resin on the Sonic Mega Phrozen printer (Figure 13). To cut the production costs and time, we decided to print the list of abbreviations using the swell paper method.

The fact that we wanted the map to be printed in one piece and the limited dimensions of the printer's build plate required a specific arrangement of the map sheet on the printer's build plate that dramatically increased the printing time, which lasted around 70 hours. We used approximately 500 ml resin. The printing time can be reduced to a few hours when using a different placement strategy and/or printing device.

Next, we post-processed the physical copy of the tactile map by cleaning it and solidifying it using the UV lamp. To protect the resin's properties (e.g. prevent color change) and increase its transparency, we have also coated the elements with transparent UV resistant acrylic paint.

Finally, we assembled the tactile map with the graphic map previously printed using a color plotter and regular paper using specially designed clamps to form a hybrid map (Figure 14). The final map's dimensions are 36 by 34 cm, and the corresponding legend is 12 by 19 cm.

3.3. Map evaluation

To better visualize how strong the generalization has to be in order to maintain tactile maps legibility, we have calculated the occurrences of particular symbol types on different map variants: the original one from the classic atlas (Cacopulos et al., 2020), the map that we generated using the presented methodology and the existing tactile map developed back in 2004 (GUGiK, & PZN, 2004). It is worth noting that on the original map, unlike on the tactile maps discussed, rock raw materials were divided

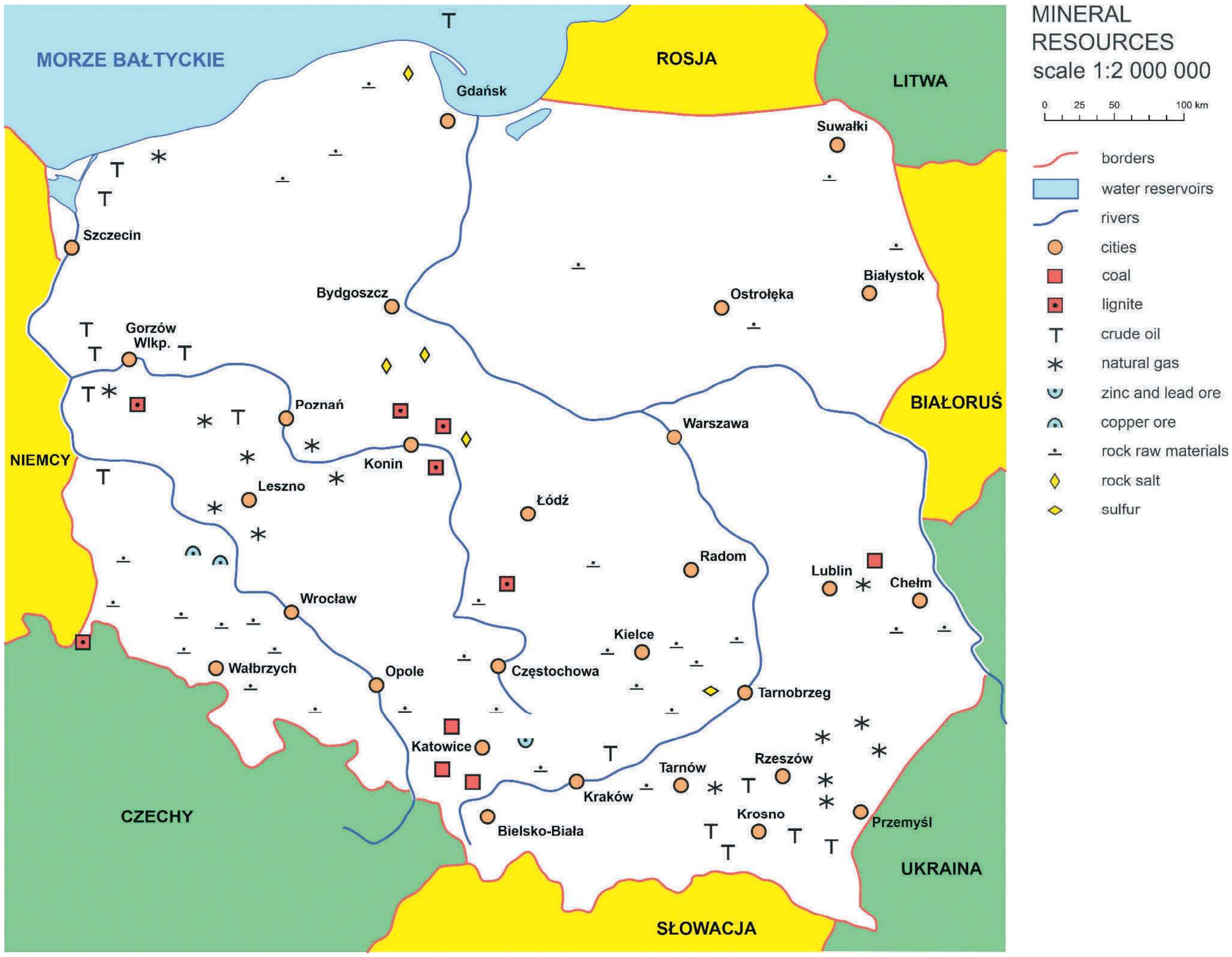


Figure 12. The final design of the graphic map variant.

into four separate categories. Apart from the symbol types shown in the graph (Figure 15), the original map also presented lakes and areas of occurrence of particular mineral resources (cf. Figure 9) that are not included in the tactile maps discussed.

The prepared map's utility and usability has been verified among 13 students of the first (nine pupils) and second (four pupils) classes aged 16–18 of the Secondary School for students with visual impairments in Laski (Towarzystwo Opieki nad Ociemniałymi w Laskach, 2022). Eight of the students had residual vision and evaluated both – the tactile and graphic contents of the map.

The non-systematic tests aimed at simulating working with a map during geography class. Students were asked to count the number of places, where particular resources are extracted (Task 1), indicate locations of extraction sites of various mineral resources in Poland (Task 2), and to describe shapes and colors of thematic symbols used on the map (Task 3). Not every student was asked to solve all the three tasks as during the map's evaluation process we were limited by the length of two lesson units (one for each class). We used the previously prepared map evaluation form to evaluate success rates of each spatial task and gather the participants' feedback on map use comfort and possible amendments of the map sheet presented. The qualitative feedback was not formally analyzed.

Task 1, e.g. count the number of sites, where coal is extracted, was solved by pupils at a success rate of 75%. The reason, why the rest of the pupils failed this task, was that they mistook symbols they were looking for with the similar ones, e.g. coal and lignite. Task 2, e.g. what resource is being extracted south-east from Warsaw, was accurately solved by 78% of pupils. The same score was achieved for Task 3, e.g. describe the shape of a symbol representing sulfur. The last result cited applies only to the tactile form. Students had troubles describing the colors used for graphic representation of symbols.

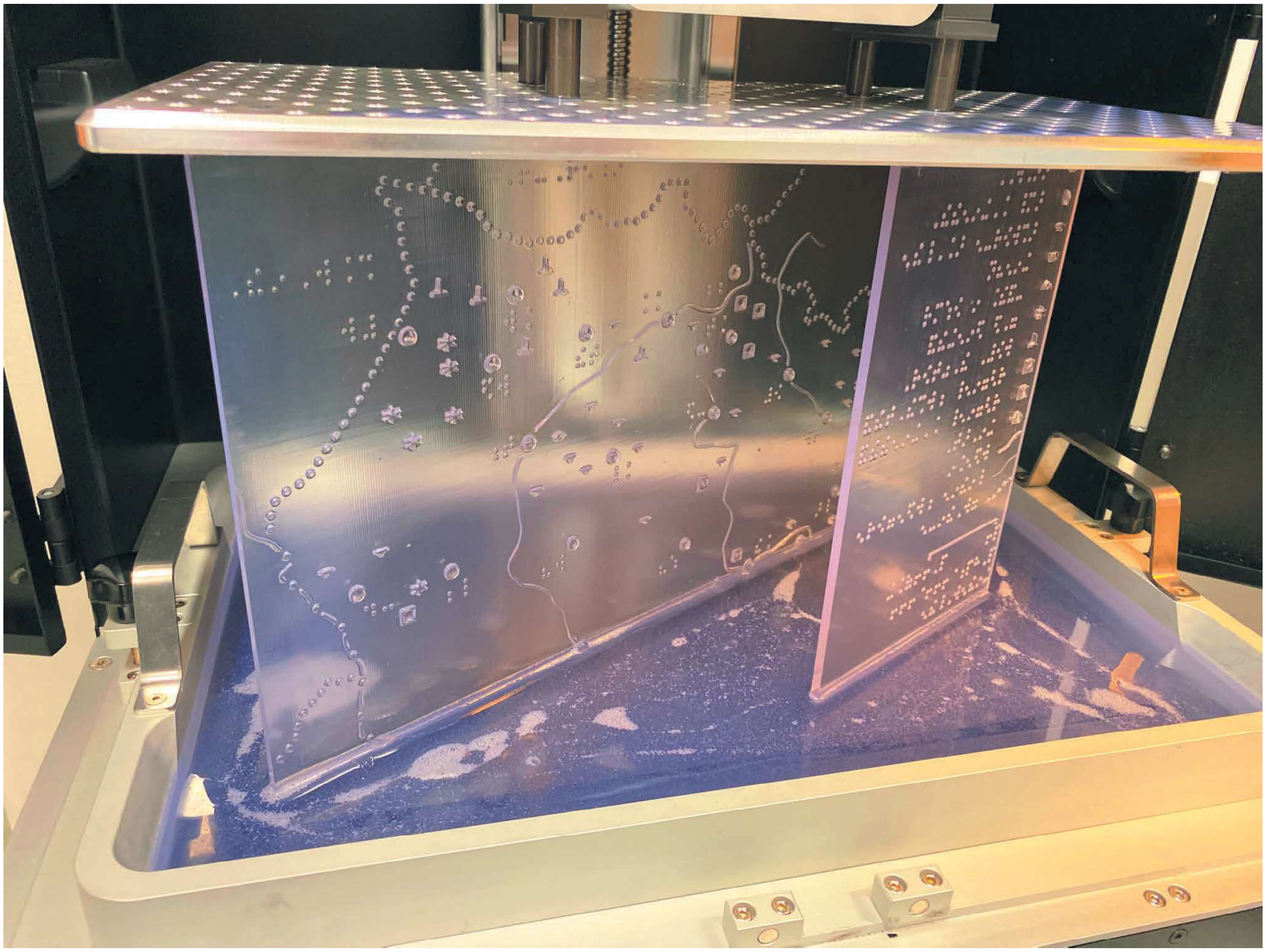


Figure 13. The stereolithography printing process using transparent resin.

The tactile content was rated as legible and comfortable to use. The material used for tactile map production was evaluated as more rigid and with sharper edges than on the maps commonly used in this school, i.e. official tactile maps occasionally issued by the Head Office of Geodesy and Cartography (e.g. Główny Urząd Geodezji i Kartografii & Polski Związek Niewidomych, 2006) that are characterized by softer tactile content due to the characteristics of the production methods used by them, e.g. thermoforming and swell paper.

But the vast majority of the study participants (83%) liked this feature as "it facilitated distinguishing particular symbols." All the symbols were tactually distinguishable, even those that are mirror reflections of each other.

However, the graphic content designed for reading using residual vision was more problematic. Five of the eight students evaluating the graphic map had troubles reading the map's content. They pointed out that the black print labels are too blurry and that the point symbols are too small – the colors applied were illegible.

The same students suggested some possible amendments that could improve the legibility. Point symbols should be bigger, and braille labels should not overwrite the black print labels – they should be placed next to each other so that the shades and light reflections caused by braille dots would not interfere with the graphic content.

The remaining three students who evaluated the graphic content were able to solve the tasks presented and distinguish colors used on the map. Two of these students were using magnifiers with additional light sources when working with the map.

4. Discussion

Our methodology is divided into a number of steps that form a parametrized pipeline and allow developing thematic tactile maps faster, cheaper, and assure their reproducibility. The case study presented proved its applicability for 3D printed hybrid tactile map used in educational setting, but we assume that it can also be used in different contexts.

Figure 14. Assembled map legend fragment. Transparent tactile layer visible over the graphic underlay.

The procedure adopted and rules on which each methodology step is based bring a direct answer to the RQ1. Adopting the anchor layers concept and establishing their hierarchy to form a repeatable background for a series of maps or thematic atlas reduces the time necessary for their development and ensures the repeatability of the base content. This solution also makes it easier for PVI to read the map, as they can focus on the thematic content.

With stable background, only the thematic content changes, so the newly emerging conflicts apply only to the thematic content. The amount of possible conflicts solutions is limited, which simplifies the map development process.

The methodology proposed can be used in two possible ways: developing tactile maps as a transcription of the existing visual maps, as well as a translation of the raw geospatial data into the form of tactile maps comprehensible by PVI. Whatever the approach, background, and thematic data can be distinguished. Background content can be created in exactly the same way regardless the approach taken. In the first case, thematic content is generalized directly from the original map – the content selection should be done earlier, during the original map creation, and it only has to be adjusted into the form legible by PVI.

In the second case, the procedure is a more complex task that includes generalization and adaptation. Using our methodology, it can be simplified by dividing it into two steps: traditional thematic content preparation (which is adequately described in the literature), and its generalization into a legible form (automated in our methodology).

Our results show that some steps of the proposed methodology can be fully automated. They are related strictly with the generalization process, i.e. selection, smoothing, alignment, and displacement. These operations must be based on unequivocal parameters. Such parameters are widely discussed in the literature as the standardization of these processes is the most desirable. This provides the answer for the RQ2 – processes of selection, smoothing, alignment, and displacement can be fully automated.

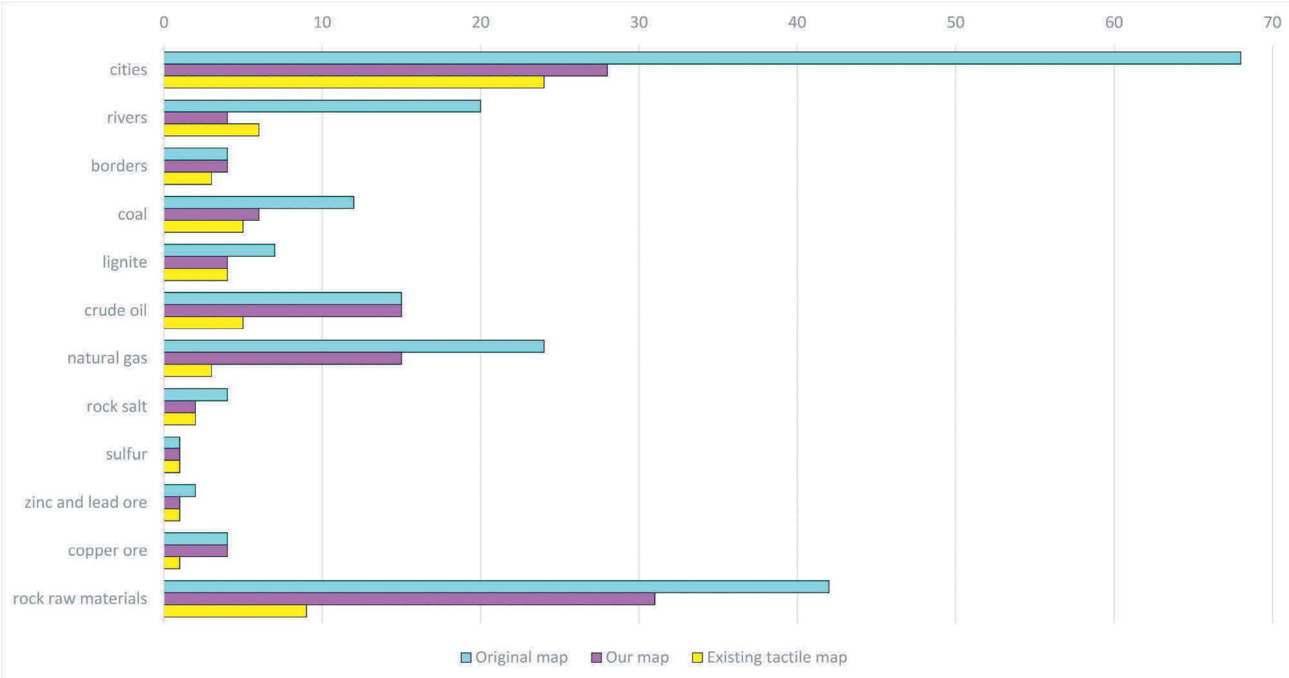


Figure 15. The occurrences of particular symbol types on the analyzed map variants.

Although not fully automatic at this point, steps of anchor layer selection, their hierarchization, map symbolization, and labeling have been profoundly described, leaving a reader with a number of rules and parameters that could be followed when developing similar tactile maps in the future. For instance, to create a similar atlas for France, the anchor layers would be similar although the selected rivers and cities would be different. There might be a layer representing mountains instead of water bodies as they are more anchoring in French geography.

The approach of using anchor layers could be used not only in thematic atlases but also in situations where a lot of content is not suitable to fit onto one map sheet. One possible solution in such a scenario is to divide the map into fragments and produce a few map sheets presenting the phenomena in a larger scale. But since the discontinuities generated might reduce the readability, a better solution is to create several maps of the same area with a higher level of generalization applied that share the common reference layers but have different thematic content presented on each map sheet (Edman, 1992).

When developing maps at different scales, of different areas, and/or using different production methods, the choice of algorithms would be somehow specific, but the overall methodology involving the global master plan seems applicable to generate various tactile maps or atlases.

For maps on larger scales, one has to deal with more area features, whereas at smaller scales, it might be necessary to conduct more radical feature simplification, even including the schematization of borders. Involving maps at various scales in a single generalization process seems to be the most complex task at this point.

When using the proposed methodology along with other than the discussed production methods, the basic assumptions of the global master plan would remain unchanged, but it would be necessary to consider the selected production method characteristics that might require different map redaction approach. For example, if the production method does not allow height differentiation of tactile signs, e.g. swell paper method, it might be necessary to increase the minimum horizontal distances between symbols. If the method selected would not allow obtaining transparency of the tactile layer, preparing a hybrid map might not be possible. The redaction parameters would have to be tweaked even when using different techniques within a 3D printing domain. For example, methods using thermoplastics are characterized by lower resolution capabilities than stereolithography. For this reason, map elements would have to be bigger and geometrically less complex.

5. Conclusions

This article presents a complete methodology for thematic tactile maps development and presents a case study confirming the validity of our proposal for educational tactile maps used in schools for children with visual impairments. The methodology can be easily parametrized and modified for future use for different user groups, in different contexts and using different production methods.

The results demonstrate the correctness and usefulness of the proposed methodology. It is possible to semi-automatically prepare a hybrid thematic tactile map, legible both using the sense of touch and/or damaged sight.

It should be used along with tactile maps development guidelines designed for specific production methods in order to accurately extract the necessary generalization parameters. We aimed at making this methodology as universal and automatic as possible but identified certain limitations while preparing a case study map that we want to handle in our future research.

The assumptions made in our Python algorithm caused some important natural resources to disappear from the final map. Additional iterations with different map topics would allow us to tweak the algorithm to perform more accurate selections of features.

Due to the limited space on the designed map sheet, some of the labels appeared too close to other features. In one case, we were unable to fit the full name of a neighboring country. We could either consider using a printing device with a larger build plate or split the map sheet into parts so that maps in a bigger scale could be produced.

At this point, the methodology requires the involvement of a number of software programs, which causes compatibility issues. We believe that the conversions and transfers between software could also be automated and scripted, forming sort of a black box for the final user.

Future research might also consider the automation of the 3D map development, i.e. the transfer from a flat vector drawing of a map to a printable solid.

The feedback obtained during the map evaluation phase would help us improve the maps produced in the future. No students complained about too little distances between particular symbols on the map, which once again confirms the hypothesis from one of our previous research (Wabiński, Śmiechowska-Petrovskij, et al., 2022). In the future, we would like to verify, whether the presented methodology would be useful for creating maps for adults by conducting a systematic human subject testing.

The students indicated that the map format is appropriate and that "it could even be bigger." We could possibly increase the map's scale to make the symbols bigger, thus improving legibility of the graphic content.

We have also scheduled additional trials to avoid the blur effect caused by inappropriate cleaning of the map sheet used in the evaluation process. This includes evaluating various printing materials and post-processing methods that we aim to describe in future research papers. This could resolve the legibility issues of the graphic underlays in the future maps.

We believe that the methodology presented in this paper forms another step toward making tactile maps development process automatic, broadening the access to tactile materials among PVI, and equalizing the accessibility to open public information.

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Data availability statement

The resulting maps in the form of both 3D models and flat vector drawings, as well as the Python algorithms used for basemap and thematic data generalization, are available at the dedicated repository: https://doi.org/10.1080/15230406.2022.2105747. The CartAGen plugin repository is available at https://doi.org/10.1080/15230406.2022.2105747.

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Warszawa, Polska

Warszawa, 31.08.2022

OŚWIADCZENIE

Niniejszym potwierdzam, że w ramach artykułu:

Wabiński, J., Mościcka, A., & Kuźma, M. (2020). The Information Value of Tactile Maps: Comparison of Maps Printed with the use of Different Techniques. The Cartographic Journal, 58(2), 123–134. https://doi.org/10.1080/00087041.2020.1721765

Byłem odpowiedzialny za zaprojektowanie badania, opracowanie metodyki, pozyskanie materiałów i wykonanie analiz. Przygotowałem manuskrypt i brałem udział w przygotowaniu odpowiedzi na uwagi recenzentów.

Mój wkład oceniam na 70% całości artykułu.

Jakub Wabiński
....
(podpis)

Albina Mościcka
Wydział Inżynierii Lądowej i Geodezji
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Warszawa, Polska

Warszawa, 31.08.2022

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Brałam udział w zaprojektowaniu badań i opracowaniu metodyki. Wykonałam korektę manuskryptu i brałam udział w przygotowaniu odpowiedzi na uwagi recenzentów.

Mój wkład oceniam na 20% całości artykułu.

Albina Mościcka
....
(podpis)

Marta Kuźma
Wydział Historii
Uniwersytet Warszawski
Warszawa, Polska

Warszawa, 29.08.2022.

OŚWIADCZENIE

Niniejszym potwierdzam, że w ramach artykułu:

Wabiński, J., Mościcka, A., & Kuźma, M. (2020). The Information Value of Tactile Maps: Comparison of Maps Printed with the use of Different Techniques. The Cartographic Journal, 58(2), 123–134. https://doi.org/10.1080/00087041.2020.1721765.

Brałam udział w zaprojektowaniu badania i opracowaniu metodyki oraz byłam odpowiedzialna za zgromadzenie materiałów źródłowych. Brałam udział w przygotowaniu odpowiedzi na uwagi recenzentów.

Mój wkład oceniam na 10% całości artykułu.

Marta Kuźma
....
(podpis)

Jakub Wabiński
Wydział Inżynierii Lądowej i Geodezji
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Warszawa, Polska

Warszawa, 31.08.2022

OŚWIADCZENIE

Niniejszym potwierdzam, że w ramach artykułu:

Wabiński, J., Śmiechowska-Petrovskij, E., & Mościcka, A. (2022). Applying height differentiation of tactile signs to reduce the minimum horizontal distances between them on tactile maps. PLOS ONE, 17(2).
https://doi.org/https://doi.org/10.1371/journal.pone.0264564

Byłem odpowiedzialny za zaprojektowanie badania, opracowanie metodyki, przygotowanie materiałów testowych, przeprowadzenie sesji badawczych i przeanalizowanie wyników. Opracowałem manuskrypt i brałem udział w przygotowaniu odpowiedzi na uwagi recenzentów.

Mój wkład oceniam na 60% całości artykułu.

....
(podpis)

Emilia Śmiechowska-Petrovskij
Wydział Nauk Pedagogicznych
Uniwersytet Kardynała Stefana Wyszyńskiego w Warszawie

Warszawa, 30 sierpnia 2022 r.

OŚWIADCZENIE

Niniejszym potwierdzam, że w ramach artykułu:

Wabiński, J., Śmiechowska-Petrovskij, E., & Mościcka, A. (2022). Applying height differentiation of tactile signs to reduce the minimum horizontal distances between them on tactile maps. PLOS ONE, 17(2).
https://doi.org/https://doi.org/10.1371/journal.pone.0264564

Byłam odpowiedzialna za zaprojektowanie sesji badawczych i ich przeprowadzenie oraz za analizę statystyczną uzyskanych wyników. Brałam udział w opracowaniu manuskryptu oraz przygotowaniu odpowiedzi na uwagi recenzentów.

Mój wkład oceniam na 30% całości artykułu.

Emilia Śmiechowska-Petrovskij
....
(podpis)

Albina Mościcka
Wydział Inżynierii Lądowej i Geodezji
Wojskowa Akademia Techniczna im. J. Dąbrowskiego
Warszawa, Polska

Warszawa, 31.08.2022

OŚWIADCZENIE

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Byłam współodpowiedzialna za opracowanie koncepcji badań. Wykonałam korektę manuskryptu i brałam udział w przygotowaniu odpowiedzi na uwagi recenzentów.

Mój wkład oceniam na 10% całości artykułu.

Albina Mościcka
....

(podpis)

Jakub Wabiński
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Wojskowa Akademia Techniczna im. J. Dąbrowskiego
Warszawa, Polska

Warszawa, 31.08.2022

OŚWIADCZENIE

Niniejszym potwierdzam, że w ramach artykułu:

Wabiński, J., Mościcka, A., & Touya, G. (2022). Tactile maps design guidelines standardization: literature and best practices review. The Cartographic Journal. https://doi.org/10.1080/00087041.2022.2097760

Byłem odpowiedzialny za zaprojektowanie badania, przeszukiwanie baz danych, przegląd zidentyfikowanych materiałów oraz ocenę ich jakości, jak również opracowanie kwestionariusza i pozyskanie odpowiedzi. Przygotowałem manuskrypt i brałem udział w przygotowaniu odpowiedzi na uwagi recenzentów.

Mój wkład oceniam na 70% całości artykułu.

....
(podpis)

Albina Mościcka
Wydział Inżynierii Lądowej i Geodezji
Wojskowa Akademia Techniczna im. J. Dąbrowskiego
Warszawa, Polska

Warszawa, 31.08.2022

OŚWIADCZENIE

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Byłam współodpowiedzialna za opracowanie koncepcji badań. Wykonałam korektę manuskryptu i brałam udział w przygotowaniu odpowiedzi na uwagi recenzentów.

Mój wkład oceniam na 20% całości artykułu.

Albina Mościcka
....

(podpis)

Guillaume Touya
LASTIG, Univ Gustave Eiffel, IGN-ENSG,
F-77420 Champs-sur-Marne, France

Champs-sur-Marne, 29/08/2022

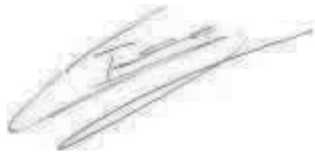
STATEMENT

I hereby confirm that my contribution in the paper:

Wabiński, J., Mościcka, A., & Touya, G. (2022). Tactile maps design guidelines standardization: literature and best practices review. The Cartographic Journal. https://doi.org/10.1080/00087041.2022.2097760

was to design the study and perform analysis of the results. I took part in preparation of the responses to the reviewers' comments.

I estimate my contribution to be 10% of the entire research.



....

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Jakub Wabiński
Wydział Inżynierii Lądowej i Geodezji
Wojskowa Akademia Techniczna im. J. Dąbrowskiego
Warszawa, Polska

Warszawa, 31.08.2022

OŚWIADCZENIE

Niniejszym potwierdzam, że w ramach artykułu:

Wabiński, J., Mościcka A. (2019) Automatic (tactile) map generation—a systematic literature review. ISPRS International Journal of Geo-Information, 8(7), https://doi.org/10.3390/ijgi8070293

Byłem odpowiedzialny za zaprojektowanie badania, przygotowanie protokołu przeglądu, przeszukiwanie baz danych, przegląd zidentyfikowanych materiałów oraz ocenę ich jakości. Przygotowałem manuskrypt i brałem udział w przygotowaniu odpowiedzi na uwagi recenzentów.

Mój wkład oceniam na 80% całości artykułu.

Jakub Wabiński
....
(podpis)

Albina Mościcka
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Wojskowa Akademia Techniczna im. J. Dąbrowskiego
Warszawa, Polska

Warszawa, 31.08.2022

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Wabiński, J., Mościcka A. (2019) Automatic (tactile) map generation—a systematic literature review. ISPRS International Journal of Geo-Information, 8(7), https://doi.org/10.3390/ijgi8070293

Byłam odpowiedzialna za przegląd zidentyfikowanych materiałów oraz ocenę ich jakości. Wykonałam korektę manuskryptu i brałam udział w przygotowaniu odpowiedzi na uwagi recenzentów.

Mój wkład oceniam na 20% całości artykułu.

....

(podpis)

Jakub Wabiński
Wydział Inżynierii Lądowej i Geodezji
Wojskowa Akademia Techniczna im. J. Dąbrowskiego
Warszawa, Polska

Warszawa, 31.08.2022

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Niniejszym potwierdzam, że w ramach artykułu:

Wabiński, J., Touya, G. & Mościcka, A. (2022). Semi-automatic development of thematic tactile maps. Cartography and Geographic Information Science
https://doi.org/ 10.1080/15230406.2022.2105747

Byłem odpowiedzialny za zaprojektowanie badania, pozyskanie materiałów, przygotowanie algorytmu do opracowania mapy podkładowej, algorytmu do generalizacji danych tematycznych, opracowanie i wydrukowanie mapy stanowiącej studium przypadku, a także za zweryfikowanie przydatności mapy w ośrodku kształcącym dzieci niewidome i słabowidzące. Opracowałem manuskrypt i brałem udział w przygotowaniu odpowiedzi na uwagi recenzentów.

Mój wkład oceniam na 70% całości artykułu.

Jakub Wabiński
....
(podpis)

Guillaume Touya
LASTIG, Univ Gustave Eiffel, IGN-ENSG,
F-77420 Champs-sur-Marne, France

Champs-sur-Marne, 29/08/2022

STATEMENT

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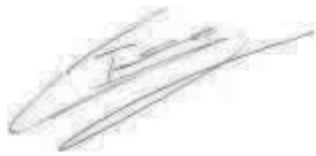
https://doi.org/ 10.1080/15230406.2022.2105747

was to design the study and prepare generalization algorithms. I made corrections to the manuscript and took part in preparation of the responses to the reviewers' comments.

I estimate my contribution to be 20% of the entire research.



....

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Warszawa, 31.08.2022

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Byłam współodpowiedzialna za opracowanie koncepcji badań. Wykonałam korektę manuskryptu i brałam udział w przygotowaniu odpowiedzi na uwagi recenzentów.

Mój wkład oceniam na 10% całości artykułu.

....

(podpis)