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# Interactive shearing for terrain visualization: an expert study

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**Abstract** Interpreting terrain in traditional 2D maps can be challenging. However, recent work has shown how interactive shearing of terrain can help users better understand topography and extract elevation information from a map. Using this approach, user input – paired with existing interactions such as pan and zoom – triggers brief ephemeral shearing animations that expose depth and shape information in terrain maps. The animations use motion to enhance the perception of depth and convey the impression of a shaking jelly model that oscillates until it comes to rest. However, it is still unclear how the parameters of these animations impact the effectiveness of the method or if the animations may have negative side effects. Moreover, it is unknown whether interactive relief shearing is accessible enough to be used in common web maps. To investigate these questions, we conducted a user study with 49 cartographers and visualization experts. These experts interactively configured shearing animations and assessed the technique's usability and applicability. To create a platform for the user study and demonstrate that interactive shearing of terrain is technically feasible in browsers, we implemented a web map with interactive shearing animations. All experts found that interactive relief shearing made it easier to see differences in elevation on orthophoto maps. Future web maps could include shearing animations, making it easier for viewers to interpret terrain and see differences in elevation.

**Keywords** Terrain maps · Depth perception · Interaction · Plan oblique relief · Expert study · Web maps

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## 1 Introduction

The interpretation of landforms in traditional orthographic maps can be challenging for many users. This has inspired cartographers to search for alternative techniques to show the third dimension of terrain. One approach is three-dimensional maps, which show terrain as viewed from an angle, rather than from above as in a traditional orthographic projection. Cartographers occasionally also combine three-dimensional and conventional orthographic maps by curving the terrain along the viewing direction [1, 2]. The resulting maps transition from an orthographic perspective in the foreground to a three-dimensional perspective in the background. Other representations such as multi-perspective maps, locally distorted terrain, or maps transitioning from a three-dimensional perspective in the foreground to an orthographic perspective in the background are also possible [3–7]. However, the various forms of interactive three-dimensional maps and virtual globes require more complex interactions for navigation and camera control than two-dimensional interactive maps. Additionally, three-dimensional views often lead to occlusions and perspective distortions that make distance and elevation estimations difficult.

An alternative method is interactive relief shearing, which was recently introduced by Willett et al. [8]. Interactive relief shearing is based on brief ephemeral animations that shear the terrain and use motion to enhance depth perception. The idea is to provide lightweight techniques that extend existing two-dimensional map interactions such as panning or zooming. The advantages of three-dimensional visualizations and motion as a visual cue for depth perception are combined with the properties of common two-dimensional maps without increasing the complexity of user interactions. In perceptual psychology, motion is known to be one of the most important sources of depth information. However, there are few examples where motion is used to communicate elevation in maps. Inspired by the work of Willett et al. [8], this article explores how interactive animated 3D relief may improve terrain perception.

Willett et al. [8] conducted a series of experiments to assess the impact of interactive relief shearing and found that interactive relief shearing helps users to better understand terrain and discern elevation in a map. In their experiments, Willett et al. used elevation comparison tasks, in which they presented participants with pairs of points and asked them to determine the higher elevation. While these experiments showed that interactive relief shearing can improve elevation discrimination, it is unclear how different degrees of shearing and elasticity impact the effectiveness of the method. To explore these questions, we created a general web-based mapping tool that implements interactive relief shearing. Our prototype expands upon Willett et al.'s relatively limited desktop implementation and demonstrates that interactive relief shearing can work smoothly and scalably in modern web browsers. We used the prototype to conduct a study in which 49 cartographers and visualization experts explored maps with interactive relief shearing.

The main goal of the study was to determine animation parameters (duration and frequency) that the experts would judge appropriate. We also wanted to obtain expert feedback regarding the usefulness and relevance of interactive relief shearing, and determine whether interactive relief shearing leads to undesired side effects such as terrain reversal effects or motion sickness.

The experts assessed the technique's usability, and interactively adjusted parameters based on their experiences. We asked study participants to assess whether general users would accept the presented technique. Furthermore, we identified potential side effects such as motion sickness and terrain reversal effects.

## 2 Related work

Our investigation builds on prior research on depth perception, as well as existing work on plan oblique relief and Willett et al.'s initial exploration of interactive relief shearing [8].

### 2.1 Depth perception

In perceptual psychology, depth perception–the ability to perceive the world in three dimensions–can be understood in terms of depth cues [9]. These cues describe the connection between visual information that can be perceived by the human eye and depth in a scene. Goldstein classifies different types of cues that signal depth into three major groups: (1) oculomotor cues are based on our ability to sense the position of our eyes and the tension in our eye muscles; (2) monocular cues work with one eye; and (3) binocular cues depend on two eyes [9].

Interactive shearing for terrain uses monocular depth cues and does not rely on three-dimensional display technologies, such as stereoscopic (using 3D glasses), autostereoscopic (glasses-free 3D) [10, 11], or holographic methods [12]. Monocular depth cues are two-dimensional and may lead to ambiguous depth information. However, the combination of multiple monocular depth cues can produce a powerful sense of three-dimensionality. Monocular depth cues can be subdivided into pictorial and movement-based cues [9].

Historically, cartographers have applied and experimented extensively with pictorial cues to represent 3D shape. For example, shaded relief–in which light and shadow communicate the shape of the terrain–is considered an extremely effective method [13]. One of the strongest depth cues is apparent size, where objects of identical physical size seem bigger when they are closer to the viewer and appear smaller when they are farther away from the viewer. Apparent size is used in 3D maps. Occlusion is another important pictorial depth cue relevant to 3D maps and interactive relief shearing. When an object partially covers another object, it must be in front of the latter, meaning the partially covered object must be farther away from the viewer.

Movement-based depth cues can only be provided when the observer or objects in the scene are moving. When the object or observer move relative to one another, parts of the object appear or become hidden based on the change in viewing angle. This deletion and accretion, or "kinetic occlusion" [9], suggests the relative shape and elevation of the occluding and occluded points. Another movement-based cue is motion parallax, which describes the effect that occurs when the viewpoint of an observer changes due to motion. Objects that are nearer to the viewer seem to move faster. The effect can be observed on a train when a tree or house close to the railroad track seems to pass by faster than a mountain range at the horizon [9]. Prior research has demonstrated that motion parallax is a very effective depth cue [14].

### 2.2 Plan oblique relief

Jenny and Patterson [15] introduced plan oblique relief as a digital projection technique to combine the advantages of three-dimensional views and traditional two-dimensional orthographic maps. Jenny and Patterson [15, p. 21] describe it as a "digital solution for [...] the standing up style of terrain presentations." Many cartographers and artists have created similar maps, using a variety of names to describe it including *proportional relief landform map*, *3D* *planimetric relief*, and *oblique orthographic shaded relief* [15]. The method is now commonly referred to as *plan oblique relief*–a name derived from the *planimetric* base and *oblique* angle.

Plan oblique relief applies a parallel projection to a digital elevation model. The image plane for a conventional map with an orthographic projection is placed horizontally above the terrain (Fig. 1, left). For creating a plan oblique map, the parallel image plane is shifted relative to the map's ground plane (Fig. 1, center). An alternative technique resulting in the same map rendering is accomplished by shifting (or shearing) every point of the terrain surface by a value based on the current angle of inclination between the planes and proportional to a point's elevation (Fig. 1, right) [16]. Therefore, locations with high altitudes are displaced further than lower points. However, because the displacement depends on the original elevation, distances between points at the same altitude are rendered without distortion. Compared to three-dimensional perspective views, plan oblique relief better preserves distances and angles. At the same time, it shows landforms from a more familiar side view compared to conventional shaded relief maps with an orthographic projection [15]. While plan oblique relief maps were traditionally static, interactive relief shearing applies ephemeral shearing animations to a map whenever a user drags or zooms the map.

## 2.3 Interactive relief shearing

Interactive relief shearing uses animations that temporarily apply relief shearing to a map, producing results that are identical to plan oblique relief. Initially, the map is shown in an orthographic projection. Direct user interactions (like dragging a point on the map with the mouse cursor) shear the model based on the speed and direction of the interaction, exposing the underlying 3D shape of the terrain. Following the interaction (when the mouse stops moving) the model animates back to its original unsheared state. The animations give the impression of a shaking jelly model that oscillates until it comes to rest. We discuss the look and feel of the animation in terms of *frequency* (of oscillation) and *duration* (time until the oscillating model comes to rest). Willett et al. [8] argue that motion, one of the most important sources of depth information, has not been used to its full potential in cartography. In response, interactive relief shearing uses multiple monocular movement-based depth cues to convey elevation. When the terrain model is sheared, back slopes of mountains or entire valleys are temporarily occluded, providing deletion and accretion cues. At the same time, the base of the model remains in place or lags behind the dragged point, producing motion parallax. Using these cues, the viewer can judge the depth of any moving point based on its relative velocity and occlusion.

Willett et al. explore multiple simple interaction methods that trigger shearing in response to existing basic 2D map interactions such as panning or zooming. Our work examines two of

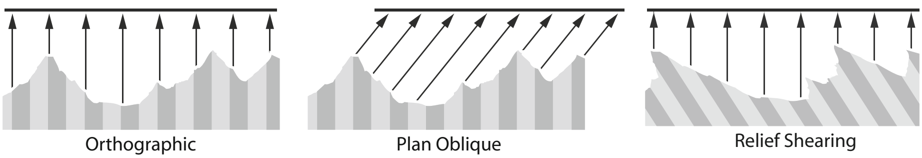


**Fig. 1** Similar to the orthographic projection (*left*), plan oblique relief uses a parallel projection, but the image plane is shifted relative to the map's ground plane (*center*). Relief shearing deforms the terrain surface and uses an orthographic projection (*right*) (after [8])

these techniques: *integrated shearing* and *hybrid shearing*. Integrated shearing deforms the terrain as the user pans the map. The terrain elastically snaps back into place whenever the drag slows or stops. Hybrid shearing also allows a user to make small motions that shear terrain while keeping the base of the model fixed. However, any drag interactions that stay within a small radius of the initial press do not engage the elastic force, allowing the user to hold the model in a sheared state and examine the sides and silhouettes of terrain features. Once the user drags outside this radius, the interaction reverts to integrated shearing, allowing the user to pan the map. Willett et al. [8, p. 3566] provide additional information illustrating the difference between integrated and hybrid shearing.

Willett et al. conducted user studies, in which they showed participants pairs of points placed on maps. Participants were asked to select the higher point from each pair. During their first test Willett et al. used three different topographic maps with different map scales and complexity, and compared orthographic maps with standard panning against maps with interactive shearing. These experiments showed that the motion cues in interactive shearing improve depth discrimination, and participants were better at differentiating elevations with interactive shearing than with static maps. In a second set of tests Willet et al. compared maps with standard panning, integrated shearing, top-down central perspective, inclined central perspective, and shearing coupled to the tilt of a tablet computer. They found that participants had the highest accuracy scores when using integrated shearing. They conclude that using interactive relief shearing improved users' ability to judge elevation and topography, and provided a "richer sense of space while preserving simplicity" [8, p. 3572].

## 3 Goals

Interactive relief shearing can help users better understand terrain representations and compare elevations on a map [8]. However, it is unclear how parameters such as the duration and frequency of the shearing animations influence the effectiveness of the technique. It is also unclear whether cartographers or general users will find interactive relief shearing in web maps useful. To investigate these issues, we conducted a study in which we presented our prototype to a range of cartographers and visualization professionals. We surveyed professionals because we hoped to utilize their expertise to identify possible positive and negative aspects of the tool, and to help calibrate parameters for use by non-professional users [17].

The main goal of the user study was to find an answer to the following question: What duration and frequency settings do experts prefer for different terrain types and scales? We hoped experts would agree on a set of parameters. We assumed experts would suggest different configurations of interactive relief shearing depending on the scale of the map (i.e. web map zoom level) and the type of terrain (such as mountainous or hilly terrain). Generally, we believed that experts would prefer shearing animations with short duration and low frequency over animation with long duration and high frequency – since these could produce distracting distortions of the terrain.

We also aimed to explore whether experts think interactive relief shearing is useful and relevant for general users. It must be noted, however, that expert studies cannot replace studies with general user subjects because expert studies cannot assess general user relevance, usefulness or performance.

Since the prototype by Willett et al. [8] was a desktop application and the technique had not been tested on the web, we intended to evaluate the viability of the techniques within modern web browsers.

Lastly, we wanted to identify the seriousness of potential side effects of interactive shearing. Willett et al. [8] found that interactive relief shearing can trigger terrain reversal, a well-known phenomenon in cartographic relief shading where terrain features such as valleys and ridges can appear inverted [18–20]. We also hoped to collect indications whether or not the technique could trigger visually induced motion sickness [21, 22] or common symptoms like nausea, dizziness, and fatigue [23].

## 4 Methods

### 4.1 Implementation

We demonstrate that interactive relief shearing can be provided as an easy-to-use interaction technique in a regular web-based map. Our prototype significantly extends Buddeberg et al.'s [24] plan oblique relief web map by implementing the shearing interactions described by Willett et al. [8], along with a number of additional improvements. The interactive relief shearing is based on the OpenLayers 3 web mapping library which we extended with a renderer for digital elevation models. We apply a technique outlined by Jenny et al. [16] for rendering plan oblique relief from a tiled terrain, using WebGL and the graphics processing unit for rapid rendering. The resulting application, the *Elastic Terrain Map*, is available online at http://elasticterrain.xyz (Fig. 2). The application's source code is publicly available on GitHub.[1]

To keep the look and feel of the interactive relief shearing animations smooth, we use a model that simulates the restoring force of a mechanical tension spring. When a user presses down on the map, the software records the coordinates of the pointer (Fig. 3). As the user drags, the terrain shears based on the angle and distance between the current position of the pointer (c) and the initial point. At the same time, the modeled spring – which is attached to the model's base below the point of the initial drag on the one side ($s_0$) and fixed to the point below the pointer on the other side ($s_1$) – stretches. When the spring is not stretched and rests in its equilibrium position, the terrain remains unsheared. The spring model described here is also used by Willett et al. [8].

The behavior of the spring model depends on two parameters: a *spring coefficient* and a *friction force*. The friction force is responsible for damping the oscillating spring, thereby controlling the duration of the animation. The spring coefficient determines the strength or stiffness of the spring and regulates the frequency of the oscillation. It is important to note that the duration and frequency cannot be derived easily because they change every time the position of the dragging pointer changes. Therefore, our study focuses on configuring the friction force and spring coefficient parameters.

The model considers the external forces (drag) and the internal forces (spring) and computes an acceleration that can be used to derive a velocity. From the velocity and the position of the model, the software computes a new position that changes the state of the spring and leads to a different acceleration in the next animation frame. The amplitude of the oscillating velocity and displacement (i.e., shearing of the terrain) decreases over time until the spring returns to its equilibrium position.

[1] https://github.com/buddebej/elasticterrain

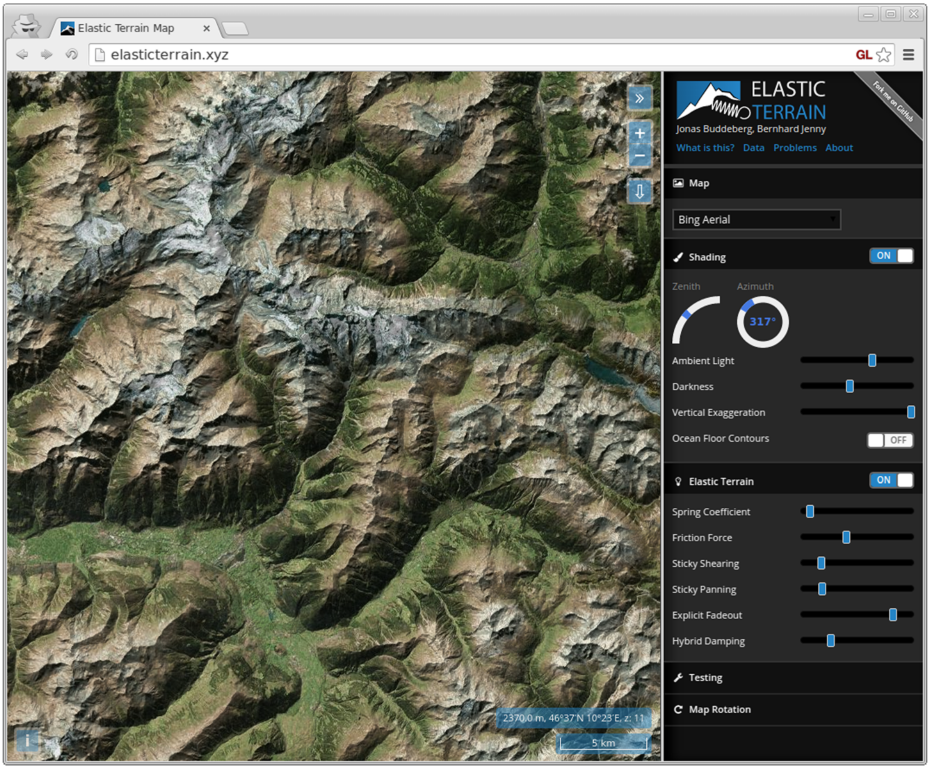


**Fig. 2** Screenshot of the *Elastic Terrain Map* prototype. A configuration panel provides different controls to customize the map rendering and experiment with the configuration of the shearing animations

## 4.2 Online study framework

To facilitate our study, we created a graphical user interface that guided participants through a series of tasks using the interactive maps (Fig. 4). To examine the relationship between different configurations of interactive relief shearing combined with different terrain features, we created a global, multi-scale dataset covering the entire planet, including bathymetry. We combined elevation data from various publicly available

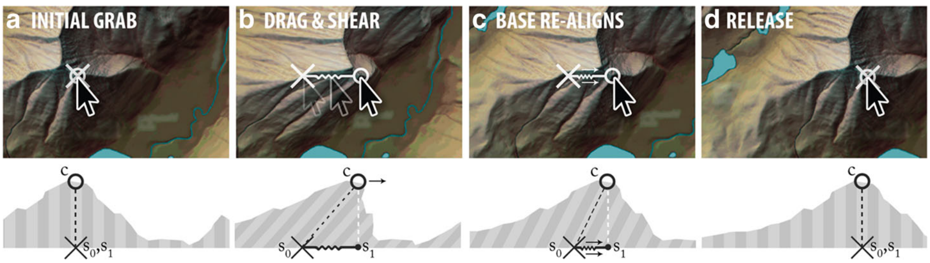


**Fig. 3** Using integrated shearing, the user grabs a point on the map (**a**) and drags it (**b**). This shears the model to keep the selected point under the cursor, while an elastic force pulls the map back into alignment (**c**). The final result (**d**) is identical to panning the map using the same motion (figure from [8])

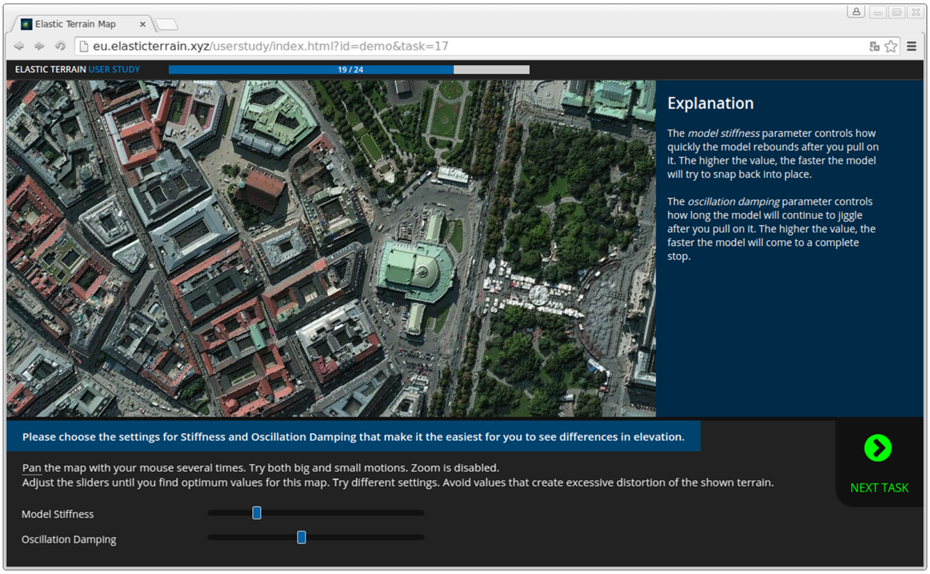


**Fig. 4** Screenshot of the user study: interactive task with slide controls to adjust configuration parameters. Parameters are explained on the right side

sources.[2] We processed the elevation models and divided them into image tiles according to the OpenGIS Web Map Tile Service Implementation Standard [25]. For the user study, we selected four scales based on the available maximum resolution of the example dataset. Zoom level 11 (approximately 1:250,000) represented large scales, while zoom level 7 (approximately 1:4000,000) represented medium scales. We also included small-scale world and continent maps at zoom level 2 (approximately 1:150,000,000). In addition, we included a spatially limited high-resolution example at zoom level 17 (approximately 1:4000).

Experiments by Willett et al. [8] applied interactive relief shearing on different topographic maps including shaded relief, contour lines, and hypsometric tints. Today, most available online map services provide street maps and aerial imagery. In response, we also included topographic maps (MapQuest) and orthophotos (Bing Aerial imagery), which we blended with shaded relief to improve the three-dimensional appearance of the terrain on orthophoto maps. To test interactive relief shearing with different terrain types, we selected two basic terrain types: high mountains and uplands. We made the map examples identical in size and limited the pannable extent of each map to a region containing a single terrain type. We also included an example of a large-scale urban surface showing buildings, trees, and bridges, and a task with bathymetric representation to solicit comments and ideas from the expert participants.

The framework tracks different parameters such as display size, average frame rate, web browser, time spent, and map interactions to gain insights about a user's experience. To ensure a similar user experience for all participants and to keep latency low, we served the application

[2] Shuttle Radar Topography Mission: https://lta.cr.usgs.gov/SRTM1Arc
General Bathymetric Chart of the Oceans: http://www.gebco.net/
Greenland Mapping Project (GIMP): http://bpcrc.osu.edu/gdg/data/icemask
EUDEM: http://www.eea.europa.eu/data-and-maps/data/eu-dem
LiDAR elevation model of Berlin: http://fbinter.stadt-berlin.de/fb/berlin/service.jsp?id=a_dgm2
LiDAR surface model of Vienna: http://www.wien.gv.at/stadtentwicklung/stadtvermessung/geodaten/dgm

using a content delivery network (Amazon CloudFront). Since the experts were located all around the world, the user study application was cached and served by multiple nodes in Australia, Asia, Europe, South America, and the United States. We required participants to run the study using a recent version of Chrome or Firefox.

### 4.3 Questions and instructions

The study included general instructions for participants. First, we informed participants of the purpose and the technical requirements of the study. We also included short explanations or guiding text for each of the individual tasks. Overall, the entire study consisted of a sequence of 23 tasks. Before they started, we asked participants for demographic information including age, gender, and country of residence.

At the beginning of the study, we instructed participants to explore a map with interactive relief shearing enabled with no limitations on zoom levels or spatial extent. The purpose of this preparatory task was to familiarize participants with interactive terrain shearing. No data from this task was analyzed.

We then collected data from four different types of tasks:

1. We showed participants a map with fixed zoom level and spatial extent, and sliders to adjust the shearing parameters. We instructed each participant to try different settings and to find the shearing parameters that they felt were optimal for the current map while avoiding excessive distortion. Each task included an explanation outlining the underlying model and describing the effect of the adjustable parameters. We asked each participant to configure shearing animations for five examples with high mountains and uplands at a large scale (zoom level 11, approximately 1:250,000) and a medium scale (zoom level 7, approximately 1:4000,000). In addition, we added one example at a very large scale (city map of Vienna, Austria at zoom level 17, approximately 1:4000) and a world/continent map at a very small scale (zoom level 2, approximately 1:150,000,000) for a total of seven examples. To ensure comparability, we did not allow participants to change the zoom level and limited the spatial extent of the maps during these tasks. We requested that participants try different settings and pan each map several times–experimenting with small and large panning moves–to identify values that made it easiest to see differences in elevation (see Fig. 4). We provided separate sliders for controlling friction force and the spring coefficient. All configuration-setting tasks used integrated shearing, that is, it was not possible for users to shear the terrain without panning the map as with hybrid shearing.
2. We asked participants a series of questions about the map interaction to assess participants' qualitative reactions. We also collected Likert-scale responses (I strongly disagree, I disagree, I agree, I strongly agree). Finally, we asked participants to discuss their experience with the prototype using free text. The exact questions are listed in Appendices Tables 1 and 2.
3. To address side effects, we asked participants to report how often they experienced terrain reversal effects or motion sickness (six ordered-categories: Always, Very Frequently, Occasionally, Rarely, Very Rarely, Never). The exact questions are listed in Appendix Table 3.
4. We presented participants with two panels showing identical maps of the same location, but with different interactive shearing parameters. We instructed participants to pan both maps using both big and small motions, but we disabled zoom and limited the maps'

spatial extent. We then asked participants to rate the extent to which given statements applied for either of the maps (Clearly left, Somewhat left, Somewhat right, Clearly right). The statements are listed in Appendix Table 4. We hoped this task would identify potential preferences for either integrated shearing (where the map pans normally and the terrain snaps back into place) or hybrid shearing (where the terrain additionally follows small user motions without panning) for different zoom levels and terrain types. Because no clear patterns could be found, we ignore these for the rest of the article.

### 4.4 Participants

We sent emails inviting experts to participate in our study. Each of the invitees has a background in cartography, visualization, or GIS. Many are members of the International Cartographic Association's Committee on Mountain Cartography, have published scientific research results related to terrain visualization, or create topographic 2D and 3D maps on a regular basis. We assigned each participant an individual URL to access the study. Participants could interrupt the study and continue at another point in time.

Among the 49 participating experts, the age distribution was as follows: 20–30 years (26.5%), 31–40 years (32.7%), 41–50 years (22.4%), and 51–60 years (18.4%). Five of the experts identified as female, 44 identified as male. On average, participants took 51.6 min to complete the study. Most participants accessed the study using Chrome (85.7%), while 14.3% used Firefox. The average number of frames per second for all participants was 56.6 (with a standard deviation of 8.0).

## 5 User study results

### 5.1 Preferred configurations for interactive relief shearing

The first task asked participants to provide settings for shearing parameters. For this task, we only counted results from experts who had tried at least two different intermediate values for each parameter before deciding on a preferred setting. We also required the participants to have panned the map multiple times for each tested value to determine the effects of that setting. Figure 5 represents the median of preferred values for spring coefficient (blue) and friction force (red) for all trials that met these criteria. The upper plot contains median parameter values for participants that panned the map at least three times; the middle plot shows values for participants with a minimum of 15 panning moves; the lower plot contains median parameter values for participants with a minimum of 30 panning moves. Participants within the first group made their decisions based on their first impression. The second group represents participants that spent some time on experimenting with different configurations. Participants within the third group made a lot of effort to determine their preferred configuration parameters. The number of observations varies for each example and group based on how many times a participant panned the map (grey bars on the left indicate the number of answers received). Each plot represents the values for all seven examples, which are denoted by a short description of the terrain type and zoom level on the y-axis. The maps are ordered by their appearance in the study. The relative preferred values for friction force and spring coefficient

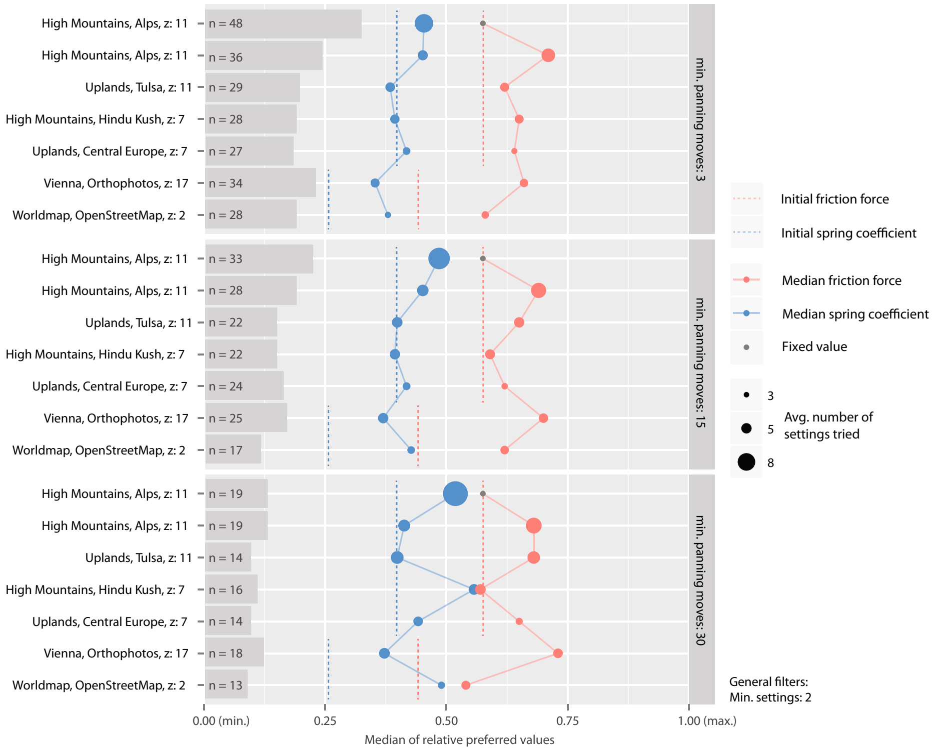


**Fig. 5** Median of preferred values for spring coefficient (blue) and friction force (red) for each test map. Number of panning moves made by participants: 3 or more in top group, 15 or more in middle group, 30 or more in bottom group. Bars on the left side indicate number of answers. The size of dots indicates the minimum average number of settings experts tested. Dashed lines represent default settings of the parameters when the test maps were loaded. Zoom level is indicated by z

are plotted on the x-axis. The dashed line indicates the predefined default values used when the test maps were loaded (note that settings were different for the very large scale and very small scale examples). The default values were determined in a pilot study. The dot size represents the minimum average number of settings experts tested. To give participants an opportunity to become familiar with the animation configuration, we showed the first task with high mountains at a large scale twice. The first time, we fixed the friction force and only allowed participants to adjust the spring coefficient. The second time, we allowed participants to adjust both the friction force and the spring coefficient.

Overall, Fig. 5 shows a high variance in the configuration values for the spring coefficient and friction force preferred by participants. We did not observe any clear relationship between the two parameters and the terrain type or zoom level. The distribution of values appears to be highly dependent on individual preference. The preferred values also do not seem to vary with the minimum number of panning moves. An exception is that users who made 30 times or more panning movements (the lower plot in Fig. 5) preferred clearly higher spring coefficients and lower friction force settings for the mountainous Hindu Kush example at zoom-level 7. This particular configuration results in relatively small terrain movements, but longer animations, which the experts of this group apparently found appropriate for the mountainous terrain of this map. However, a similar pattern does not exist for the second map, which also covered mountainous terrain. It is interesting to note that users who made 30 or more panning movements seem to prefer asymmetrical settings, that is, low spring coefficients are combined with high friction forces and vice versa.

## 5.2 Relevance, acceptance, and application

After participants had completed the study tasks, we asked them to assess the usability and relevance of interactive relief shearing for general users. Figure 6 shows that the majority of participants rated interactive relief shearing as potentially useful for general users in common web maps (89.8% agreed or strongly agreed) and considered it a convenient extension to conventional map panning (93.3% agreed or strongly agreed). We asked all participants to estimate the relevance, acceptance, problems, and areas of application for interactive relief shearing with free text comments. We then classified and summarized the results, which we present below. The number in parentheses after each statement represents the number of experts, out of the 49 total participants, who supported the statement. To ensure anonymity among participants, we use the masculine pronoun exclusively.

The majority of participants reported that they thought interactive relief shearing could be helpful for general users to perceive elevation and the shape of terrain. Three participants argue that interactive relief shearing might be more useful for general users than professional map readers because experienced users are already more accustomed to extracting elevation information from conventional forms of representation (e.g., shaded relief, contours, and hypsometric colors). Participants emphasized that interactive relief shearing allows users to gather information about elevation in a map very quickly (5) and intuitively (4). Relief shearing is particularly suitable for providing an overview or initial impression (4) of the terrain in an unknown area, or revealing otherwise hidden terrain features (3). These comments are encouraging, however, it must be emphasized that our expert studies cannot assess relevance or usefulness for general users. A follow-up study with general users is required to verify the experts' assessments.

Two experts mentioned virtual globes such as Google Earth as a possible alternative, but found that interactive relief shearing was easier to navigate. One participant explained how relief shearing enabled him to perceive the terrain in three dimensions, whereas otherwise he could not see 3D because of a visual impairment: "I cannot see 3D due to a lazy eye. [The orthophoto example] was so revolutionary to me that I can only imagine this is what 3D maps look like for those who can see 3D. I loved it! I think the reason it worked so well for me was that my eyes can determine depth via movement, not necessarily stereoscopic viewing. Awesome. I could look at this all day long!"

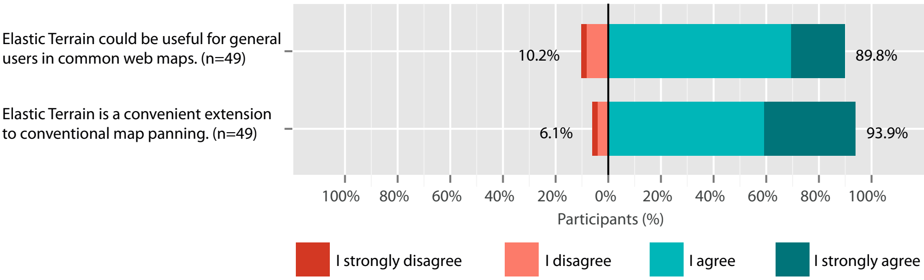


**Fig. 6** Acceptance and relevance of interactive relief shearing in web maps

## 5.3 Problems

Participants mentioned various disadvantages, uncertainties, and problems related to the presented technique. Some saw potential for distraction and disorientation (13) due to excessive or inappropriate application, or improper configuration of the oscillation. Others mentioned that the oscillation can appear comical and might be unsuitable for serious applications. Several participants noted that it takes time to get used to the animated terrain (5): "After using the tool a while, I began to intuitively use the movement to identify the terrain differences and became less distracted by the unfamiliar nature of the distorted movements"; "It might be a surprising effect at first for the general user, which might take just a bit of getting used to." One participant expressed that he generally experienced a lack of control: "Perhaps I am simply reacting negatively to the unfamiliar, but it wasn't something I'd like to encounter in day-to-day web map use. The map, as it wobbles, moves when I try to read it. I'm used to how slippy maps move in response to my panning; this moves differently, and keeps moving beyond when I release the mouse, giving me a feeling of lack of control."

## 5.4 Areas of application

Some experts believed that interactive relief shearing should only be applied to maps where terrain is an important component, not for general purpose maps (3). Participants suggested different areas of potential application such as outdoor or recreation maps (4), educational purposes (2), communication of natural hazards, tourist maps, multidimensional thematic maps, and the visualization of other surfaces or data (3). In general, participants indicated that the suitability and effectiveness of interactive relief shearing may vary with the structure of terrain, the type of map used, and scale.

**Suitability for different map scales** During the study, we displayed most examples at large (zoom level 11) and medium scales (zoom level 7). We then asked participants to comment on two more examples, one at a small scale (zoom level 2, world/continent) and one at a very large one (zoom level 17, city orthophoto map of Vienna). Many participants noted that the effectiveness of interactive relief shearing seemed dependent upon scale and that the best results were generally produced at large scales (23): "I think [interactive relief shearing] is more effective at larger scales, not to say that it isn't effective at small scales, it just seems more dramatic and effective [...], although for something like a local city map, I think it is a bit unnecessary." Participants found that interactive relief shearing made it easier to perceive changes in elevation in maps with small scales, i.e., world or continent maps (27). Some mentioned that interactive relief shearing seemed less effective at small scales because it only emphasized extreme differences in terrain (5). Others stated that it seemed very effective for representing bathymetric features and large mountain ranges or plateaus at small scales (9).

We also asked participants to comment on the suitability of interactive relief shearing for visualizing bathymetry. The majority of experts agreed that the presented technique seemed particularly effective and well suited for representing bathymetry (41): "Most definitely it makes it easier to perceive changes in elevation on bathymetric maps. Ocean floor topography is an unfamiliar environment to many map readers with terrain structures that are quite different than land. The elastic movement helps differentiate up from down in complex areas, such as the mid Atlantic Ridge fracture zone. And ocean trenches look truly deep."

For the large-scale city map, most participants found that the application of interactive relief shearing made it easy to perceive changes in elevation (28). "[Interactive relief shearing] with the modeled buildings creates a very interesting and useful effect, especially in areas where drastic height differences exist between different buildings." However, many participants argued that the method might be less suitable for this scale and topography when compared to the other maps (18). Some clearly expressed that interactive relief shearing seemed entirely unsuitable for large-scale city maps (5): "Not really [helpful]. Distracting more than useful (and I'd question when there is a requirement to judge building heights by panning an aerial shot anyway). Are the buildings on the left taller than the ones on the right? I've no idea. Only large differences are evident." Several participants noted that they experienced disorientation, motion sickness (3), and terrain reversal (2) more often for the large-scale city map than for other examples.

**Suitability for different terrain types** Regarding variations in the efficiency of interactive relief shearing for different types of terrain, a few participants believed it seemed most useful in locations with less topographic variability (5): "[Interactive relief shearing] is most useful where the terrain is simple and/or subtle. [...] where there is a lot of topographic variability, the wiggling does not help as much. However, [for] prominent and singular ridges/ranges with wider flat valleys, the wiggling helps to read the terrain a lot." Another agreed: "[Interactive relief shearing is not exceedingly useful] where the terrain is very complex. But in places where there is a lot of elevation change from valley floor to ridge top and the surrounding terrain is relatively simple, it certainly makes elevation easier to discern." One participant stated that the method could be particularly useful "[...] for large smoothly varying features where local shaded relief does not show elevation change."

**Suitability for different map types** Figure 7 indicates the majority of participants agreed or strongly agreed that interactive relief shearing makes it easier to perceive changes in elevation for all presented maps. For the examples provided, interactive relief shearing worked best with the orthophoto map (100% agreed or strongly agreed), followed by the hypsometric map (92.3% agreed or strongly agreed), and the topographic map (86.5% agreed or strongly agreed). Some participants mentioned that it seemed every map type could be combined with interactive relief shearing to improve shape discrimination (3), and that differences in the helpfulness of Elastic Terrain were related more to variations in scale (12). Others emphasized

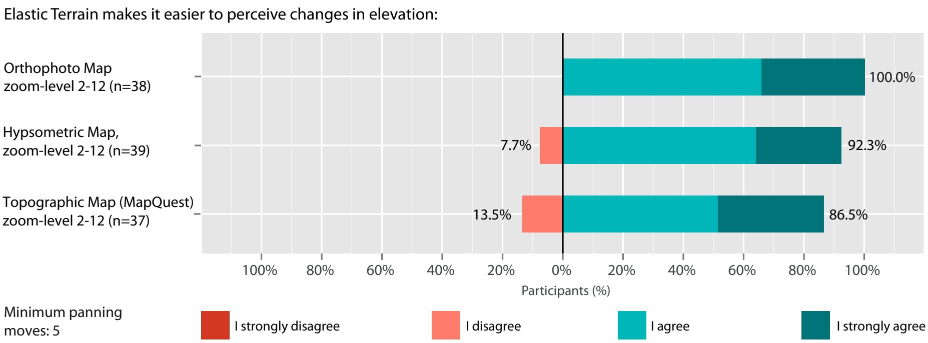


**Fig. 7** Interactive relief shearing with different types of maps. Results for each map are filtered to show only participants that panned the map at least five times

that the method seemed particularly suitable for orthophoto maps because it could overcome potential confusion with shadows and terrain reversal effects. One participant pointed out that "[Interactive relief shearing] seems to help in the orthophotos primarily in areas where differences in elevation are more subtle or where the topography is less varied." Several thought the shearing animations could hinder the readability for topographic or hypsometric maps (3) to a greater extent than for aerial imagery.

## 5.5 Suggested improvements and ideas

Many participants suggested modifications and improvements for the presented method. The most frequent suggestion was to make the oscillations subtler (21), followed by the option to turn interactive relief shearing on and off on demand (11): "I can see having it as a default panning option on most web maps with terrain (especially in satellite image mode) provided that there is a convenient and obvious way of turning it off. I would recommend using only slight amounts of jiggling, which can be annoying and distracting when set too high." Two participants suggested implementing animations attached to zoom interactions.

## 5.6 Terrain reversal effects

We asked all experts to report how often they experienced terrain reversal for local maximum and minimum points within a limited spatial extent. In this task, the participants performed multiple panning movements for an example with high mountains at zoom level 11 on a topographic map. We instructed participants to drag valleys and peaks multiple times and report how often they experienced terrain reversal effects. To identify potential variations in different shearing methods, we tested both integrated shearing (where the map pans normally and the terrain snaps back into place) and hybrid shearing (where the terrain is sheared to follow small user motions without panning, but pans for large user motions). Figure 8 shows that the majority of participants never or very rarely experienced terrain reversal effects. Across all of the maps we used, the percentage of users that experienced terrain reversal effects ranged from 20.4% to 32.7% (the sum of Rarely, Occasionally, Very Frequently, and Always). We found similar results for both shearing methods and for high and low elevations.

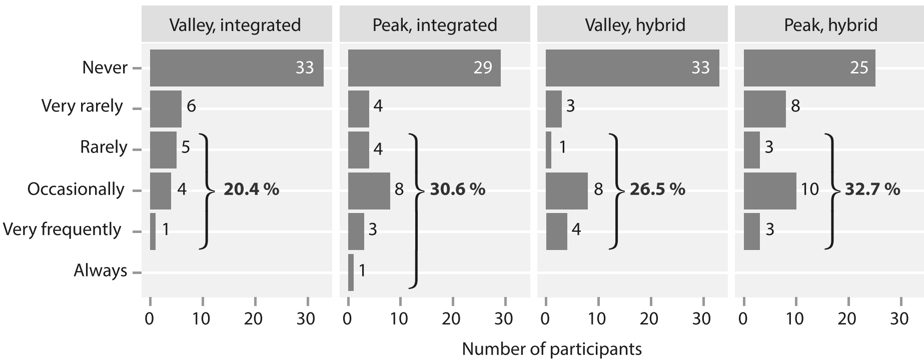


**Fig. 8** Frequency of terrain reversal effects on a topographic map at zoom level 11 in a mountainous area ($n$ = 49). Valley/peak = participants dragged at local minimum or maximum elevations; integrated/hybrid = participants used integrated shearing or hybrid shearing

In the free text comments, three users pointed out that interactive relief shearing might actually help prevent terrain reversal effects, particularly when combined with satellite imagery.

### 5.7 Motion sickness

To examine the potential for visually induced motion sickness, we asked participants if and how often they experienced motion sickness during the study. Most did not experience any; but 35.7% of participants reported some level of motion sickness. We also asked participants to further explain any effects they experienced. Most stated they did not experience any motion sickness (33), but some complained about disorientation or optical confusion (7). Three mentioned they experienced motion sickness for the first tasks before they got used to the interaction techniques. Several participants anticipated motion sickness occurring, but did not experience any (10). Some also pointed out that the occurrence appeared to be related to the distance and speed of the panning interactions (3): “Strong, fast panning of large scale high relief maps posed the most problems for me in disorientation or feelings of motion sickness. Minimal, but noticeable.” Participants noted that the effect seemed related to the configuration of the animation (6): “Motion sickness occurs when parameters are not properly tuned, and the terrain wobbles too much. If parameters are configured with a conservative approach it is not a problem I think.” Two of the participants noted that their motion sickness occurred when the animation behaved unexpectedly: “Most of the motion sickness seemed to occur when lower elevations were displaced more than the neighboring high elevations” and, “It makes me a bit dizzy when the ground is displaced more than the building tops.” Another participant suggested there could be a connection to the structure of the visible terrain “I don’t usually suffer from sea-sickness, but the wobble wobble wobble of high spots is weird. Especially the plains that shouldn’t wobble but do because of the ocean bathy [metry].” Three participants mentioned that the potential for motion sickness seemed greater for the large-scale city map: “The sickness effect is much stronger than on [the other] maps and the animation is more annoying, which makes it harder to perceive heights. Therefore I’m not sure on the usefulness for city models.”

## 6 Discussion

### 6.1 Preferred configurations for interactive relief shearing

According to Willett et al. [8, p. 3566], in their experience “[...] the oscillation produced by using a stronger spring and less [friction force] provides a satisfying conclusion to panning operations, and the additional motion at the end helps persist the depth effect.” However, our results do not reveal clear patterns indicating specific preferences for different terrain, scales, and maps. Generally, experts prefer brief and subtle animations (higher friction force values). Relative to the default settings, many chose higher friction force values and oscillations with lower durations. Moreover, it seems other participants found the default maximum value for the friction force to be too low. Preferences for the spring coefficient do not follow a clear pattern. In later trials, many participants spent less time adjusting parameters. This could be the result of learning effects or retaining similar preferences for subsequent tasks. One expert mentioned that he found the spring configuration tasks to be very tiring, which could be another possible explanation for why parameters were adjusted less often in later trials. Future studies might instruct participants to choose configuration values from a limited set of predefined values instead of continuous scales.

Generally, preferences for configuring the spring are related to an individual's panning behavior. It may be beneficial to experiment with configuration values that adapt to an individual's method of panning as they interact with the map. The software could remember a user's habits and choose values for friction force and spring coefficient based on previous interactions. For example, if a user navigates on a small-scale map to get an overview, performing relatively fast and large panning movements, the animation could be attenuated. However, the oscillation could be amplified when the user interacts with a terrain feature at a large scale, performing only small and frequent drags in different directions.

### 6.2 Feasibility, acceptance, and application

Our prototype shows that interactive relief shearing for web maps is clearly feasible from a technical point of view. The participants reached on average 56.6 frames per second and none reported major technical problems. Our prototype served as a reliable basis for the user study and we were able to demonstrate that interactive relief shearing can work smoothly and scalably in modern web browsers.

The experts largely accepted interactive relief shearing as a useful extension to conventional panning. Moreover, they agreed that it is effective, intuitive to navigate, helpful, and relevant for general users and web maps showing terrain. However, many agreed that it takes time to get used to the technique. Map readers might not be used to similar visualizations, particularly because there are only a few past examples in which cartographers have applied movement based depth cues. Several experts expressed concerns about potential distraction or disorientation. Some participants also suggested using and configuring interactive relief shearing carefully and examining its suitability for individual applications.

We believe interactive relief shearing can be offered as an optional interaction method for web maps that could be turned on and off on demand. Experts recommend its use for maps at large or medium scales (less suitable for city and world maps). Some participants commented that interactive relief shearing is most suitable for locations with little topographic variability and prominent landforms. Our participants emphasized that interactive relief shearing creates fascinating representations of bathymetric features. According to our experts, interactive relief shearing is most effective on orthophoto maps.

### 6.3 Potential side effects

Approximately 20% of the participants experienced terrain reversal effects within the scope of the user study. Experiments by Bernabé-Poveda and Çöltekin [18] suggest that many people experience terrain reversal effects when viewing terrain maps, however there are no statistics measuring how frequently they occur. It remains uncertain if and why interactive relief shearing triggers terrain reversal effects, or how this compares to existing approaches like relief shading. In fact, some experts mentioned that shearing animations might actually help users overcome confusion with shadows in aerial images. Interactive relief shearing might also prevent terrain reversal effects in certain situations such as orthophoto maps with southeast illumination.

Obtrusive oscillations, resulting from animation parameter configurations and map panning habits, can cause motion sickness. However, most of our participants commented that they did not feel any motion sickness, though some experienced disorientation or distraction. Very few participants complained about dizziness or fatigue. While the experts explored extreme parameter settings, we expect motion sickness and similar effects to occur less frequently with settings appropriate for general map use.

## 7 Conclusion

Interactive relief shearing is an innovative approach that combines the advantages of three-dimensional visualizations and common two-dimensional interactive maps without increasing the complexity of user interactions. This approach conveys a three-dimensional impression of terrain through different movement-based visual cues. By extending conventional map interactions like panning, the technique provides a simple and direct way to control the shearing animation and navigate the map.

The results of the research confirm that the technique can be successfully incorporated into common web maps. The prototype performs well in all major web browsers and on different platforms and devices. Our review yielded a strong expert agreement on the general utility of the technique. Of all the participants, 89.8% agreed or strongly agreed that interactive relief shearing could be useful for general users in common web maps. 93.3% agreed or strongly agreed that the technique is a convenient extension to conventional map panning. These findings are encouraging, however, the fact that the experts agree on these statements does not mean that interactive terrain shearing is actually more useful for general map users than conventional maps. Follow-up studies are needed to evaluate this hypothesis.

We believe a variety of different tasks related to the representation of elevation and topography in maps can benefit from the technique. Based on our initial study, we believe suitability varies for different types of terrain, scales, and for various maps. Results of our expert study indicate that 83.7% of the experts found that the presented technique was particularly effective and well suited to represent bathymetry. There was a complete agreement (100% of experts) that interactive relief shearing helps reveal depth information on orthophoto maps. However, inappropriate configurations can lead to negative side effects. Users may encounter terrain reversal effects, motion sickness, disorientations, or distractions that could impact their ability to read maps properly.

Generally, 42.9% of experts would make the oscillations subtler than our initial default oscillations. Within the scope of this article, it was not possible to identify ideal settings for specific types of terrain at varying scales in combination with different map types. This topic should be explored in further research. Ideally, the look and feel of the animations should be adapted automatically by the implementation depending on the visible terrain, the scale or the type of the base map, and individual navigation habits. Future web map services could provide shearing animations attached to map panning or zooming as an additional navigation technique to make it easier to interpret terrain and see differences in elevation.

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## Appendix: Questions asked

**Table 1** Map types

| | | | |
|---|---|---|---|
| Instruction | Please rate how strongly you agree or disagree with the statements below. | | |
| Question/Statement | Elastic Terrain makes it easier to perceive changes in elevation on this orthophoto map. | | |
| Input/Options | I strongly disagree, I disagree, I agree, I strongly agree | | |
| Location | Iceland | Terrain type | High mountains |
| Map | Bing Aerial Imagery | Zoom level | 9 (zoomable 2–12) |
| Question/Statement | Elastic Terrain makes it easier to perceive changes in elevation on this hypsometric map. | | |
| Input/Options | I strongly disagree, I disagree, I agree, I strongly agree | | |
| Location | California Pacific Coast | Terrain type | High mountains, Coast |
| Map | Hypsometric colors | Zoom level | 7 (zoomable 2–12) |
| Question/Statement | Elastic Terrain makes it easier to perceive changes in elevation on this topographic map. | | |
| Input/Options | I strongly disagree, I disagree, I agree, I strongly agree | | |
| Location | Worldwide | Terrain type | World map |
| Map | MapQuest road map | Zoom level | 3 (zoomable 2–12) |
| Instruction | None | | |
| Question/Statement | Do you have comments about Elastic Terrain in combination with different map types? Please refer to the shown examples for orthophotos (A), the topographic map (MapQuest) (B) and hypsometric colors (C). Do you think other map types could be combined with Elastic Terrain? | | |
| Input/Options | Text input | | |
| Instruction | None | | |
| Question/Statement | Do you think Elastic Terrain could make it easier to perceive changes in elevation on bathymetric (ocean floor) maps? | | |
| Input/Options | Text input | | |
| Location | Bay of Biscay | Terrain type | High mountains |
| Map | Hypsometric and bathymetric colors | Zoom level | 6 (zoomable 2–12) |
| Instruction | None | | |
| Question/Statement | Do you think Elastic Terrain could make it easier to perceive changes in elevation on large-scale city maps? | | |
| Input/Options | Text input | | |
| Location | Vienna | Terrain type | Buildings |
| Map | Bing Aerial Imagery | Zoom level | 17 (zoomable 15–17) |
| Instruction | None | | |

**Table 1** (continued)

| | | | |
|---|---|---|---|
| Question/Statement | Do you think Elastic Terrain could make it easier to perceive changes in elevation on maps with small scales, i.e. world or continent maps? | | |
| Input/Options | Text input | | |
| Location | Worldwide | Terrain type | World map |
| Map | OpenStreetMap | Zoom level | 2 (fixed) |

**Table 2** General

| | |
|---|---|
| Instruction | Please rate how strongly you agree or disagree with the statements below. |
| Question/Statement | Elastic Terrain is a convenient extension to conventional map panning. |
| Input/Options | I strongly disagree, I disagree, I agree, I strongly agree |
| Question/Statement | Elastic Terrain could be useful for general users in common web maps. |
| Input/Options | I strongly disagree, I disagree, I agree, I strongly agree |
| Instruction | None |
| Question/Statement | To what extent could Elastic Terrain be relevant for general users and map services? Please let us know your comments, improvements, and ideas. |
| Input/Options | Text input |

**Table 3** Terrain reversal effects and motion sickness

| | | | |
|---|---|---|---|
| Instruction | Please complete the tasks below and report the occurrence of terrain reversal effects. | | |
| Question/Statement | Drag the red street in the valley back and forth several times. Terrain reversal occurred: | | |
| Input/Options | Always, Very Frequently, Occasionally, Rarely, Very Rarely, Never | | |
| Shearing Method | Hybrid Shearing | | |
| Location | Alps, Ticino | Terrain type | High mountains |
| Map | MapQuest road map | Zoom level | 11 (fixed) |
| Question/Statement | Drag a high peak back and forth several times. Terrain reversal occurred: | | |
| Input/Options | Always, Very Frequently, Occasionally, Rarely, Very Rarely, Never | | |
| Shearing Method | Integrated Shearing | | |
| Location | Alps, Ticino | Terrain type | High mountains |
| Map | MapQuest road map | Zoom level | 11 (fixed) |
| Instruction | Did you experience motion sickness during the completion of this study? | | |
| Question/Statement | I experienced motion sickness: | | |
| Input/Options | Always, Very Frequently, Occasionally, Rarely, Very Rarely, Never | | |
| Question/Statement | Comments on experienced motion sickness. | | |
| Input/Options | Text input | | |

**Table 4** Statements for collecting comments on integrated vs. hybrid shearing

| | | | |
|---|---|---|---|
| Instruction | None | | |
| Question/Statement | Which of these two maps makes it easiest for you to see differences in elevation and interpret the structure and shape of the terrain? | | |
| Input/Options | Clearly left, Somewhat left, Somewhat right, Clearly right | | |
| Shearing Method (Left) | Integrated Shearing | Shearing Method (Right) | Hybrid Shearing |
| Location | Alps, Ticino | Terrain type | High mountains |
| Map | MapQuest road map | Zoom level | 11 (fixed) |
| Question/Statement | Which of these two maps makes it easiest for you to see differences in elevation and interpret the structure and shape of the terrain? | | |
| Input/Options | Clearly left, Somewhat left, Somewhat right, Clearly right | | |
| Shearing Method (Left) | Integrated Shearing | Shearing Method (Right) | Hybrid Shearing |
| Location | Central Europe | Terrain type | Lowlands / Uplands |
| Map | MapQuest road map | Zoom level | 7 (fixed) |
| Question/Statement | Which of these two maps makes it easiest for you to see differences in elevation and interpret the structure and shape of the terrain? | | |
| Input/Options | Clearly left, Somewhat left, Somewhat right, Clearly right | | |
| Shearing Method (Left) | Integrated shearing | Shearing Method (Right) | Hybrid shearing |
| Location | Hindu Kush | Terrain type | High mountains |
| Map | MapQuest road map | Zoom level | 7 (fixed) |
| Question/Statement | Which of these two maps makes it easiest for you to see differences in elevation and interpret the structure and shape of the terrain? | | |
| Input/Options | Clearly left, Somewhat left, Somewhat right, Clearly right | | |
| Shearing Method (Left) | Integrated shearing | Shearing Method (Right) | Hybrid shearing |
| Location | Tulsa, Oklahoma | Terrain type | Lowlands |
| Map | MapQuest road map | Zoom level | 11 (fixed) |

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