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Situated Visualization in Motion

Visualisation Localisée en Mouvement

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Title: Situated Visualization in Motion

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Abstract: In my thesis, I define visualization in motion and make several contributions to how to visualize and design situated visualizations in motion.

In situated data visualization, the data is directly visualized near their data referent, *i.e.*, the physical space, object, or person it refers to [1]. Situated visualizations are often useful in contexts where the data referent or the viewer does not remain stationary but is in relative motion. For example, a runner is looking at visualizations from their fitness band while running or from a public display as they are passing it by. Reading visualizations in such scenarios might be impacted by motion factors. As such, understanding how to best design visualizations for dynamic contexts is important. That is, effective and visually stable situated data encodings need to be defined and studied when motion factors are involved.

As such, I first define visualization in motion as visual data representations used in contexts that exhibit relative motion between a viewer and an entire visualization. I classify visualization in motion into 3 categories: (a) moving viewer & stationary visualization, (b) moving visualization & stationary viewer, and (c) moving viewer & moving visualization. To analyze the opportunities and challenges of designing visualization in motion, I propose a research agenda. To explore to what extent viewers can accurately read visualization in motion, I conduct a series of empirical perception studies on magnitude proportion estimation. My results show that people can get reliable information from visualization in motion, even if at high speed and under irregular trajectories. Based on my perception results, I move toward answering the question of how to design and embed visualization in motion in real contexts. I pick up swimming as an application scenario because swimming has rich, dynamic data. I implement a technology probe [2] that allows users to embed visualizations in motion in a live swimming video. Users can adjust in real-time visual encoding parameters, the movement status, and the situatedness of visualization. The visualizations encode real swimming race-related data. My evaluation with designers confirms that designing visualizations in motion requires more than what traditional visualization toolkits provide: the visualization needs to be placed in-context (*e.g.*, its data referent, its background) but also needs to be previewed under its real movement. The full context with motion effects can affect design decisions. After that, I continue my work to understand the impact of the context on the design of visualizations in motion and its user experience. I select video games as my test platform, in which visualizations in motion are placed in a busy, dynamic background but need to help players make quick decisions to win. My study shows there are trade-offs between visualization's readability under motion and aesthetics. Participants seek a balance between the readability of visualization, the aesthetic fitting to the context, the immersion experience the visualization brings, the support the visualization can provide for a win, and the harmony between the visualization and its context.

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Mots clés: Visualisation située, visualisation intégrée, perception, conception de visualisation, analyse sportive, jeux vidéo

Résumé: Dans ma thèse, je définis ce qu'est la visualisation en mouvement et j'apporte plusieurs contributions sur la manière de visualiser et de concevoir des visualisations localisées en mouvement.

Dans la visualisation localisée de données, les données sont directement visualisées à proximité de l'espace physique, de l'objet ou de la personne auxquels elles se réfèrent [1]. Les visualisations localisées sont souvent utiles dans des contextes où le référent des données et l'observateur sont en mouvement relatif. Imaginez, par exemple, un coureur regardant une visualisation sur un bracelet de fitness qu'il porte ou sur un écran public alors qu'il passe devant. De tels scénarios d'utilisation mobile et dynamique peuvent affecter la lecture de visualisations localisées. Il est donc important de comprendre comment optimiser la conception des visualisations pour ces contextes. En d'autres termes, il est d'abord nécessaire de définir des encodages de données localisées efficaces et visuellement stables; puis de les étudier lorsque des facteurs de mouvement sont impliqués.

A ce titre, je définis d'abord la visualisation en mouvement comme des représentations de données visuelles utilisées dans des contextes qui présentent un mouvement relatif entre un observateur et une visualisation entière. Je classe la visualisation en mouvement en trois catégories : (a) observateur en mouvement et visualisation stationnaire, (b) visualisation en mouvement et observateur stationnaire, et (c) observateur et visualisation tous deux en mouvement. Pour analyser les opportunités et les défis de la conception de visualisations en mouvement, je propose un agenda de recherche. Pour commencer, j'explore avec quelle précision les observateurs peuvent lire une visualisation en mouvement. A cette fin, je mène une série d'études empiriques sur la perception de l'estimation de la proportion de la magnitude. Mes résultats montrent que les participants peuvent obtenir des informations fiables à partir de visualisations en mouvement, même s'ils se déplacent à grande vitesse et selon des trajectoires irrégulières. Sur la base de mes résultats de perception, je cherche à répondre à la question de savoir comment concevoir et intégrer la visualisation en mouvement dans des contextes réels. J'utilise la natation comme scénario d'application, car la natation possède des données riches et dynamiques. J'implémente un outil de prospection technologique [2] qui permet à des concepteurs d'intégrer les visualisations en mouvement à une vidéo de natation. Les concepteurs peuvent modifier en direct les encodages visuels, l'état de mouvement ainsi que l'emplacement des visualisations. Les visualisations utilisent des données réelles liées à la course. Mon évaluation montre que la conception de visualisations en mouvement nécessite plus que ce que proposent les outils de conception de visualisations traditionnelles : la visualisation doit être placée dans son contexte (par exemple, son référent de données, son arrière-plan) mais doit également pouvoir être prévisualisée avec son déplacement réel. Le contexte complet avec les effets de mouvement peut affecter les décisions de conception. Ensuite, je continue à travailler pour comprendre l'impact du contexte sur la conception de visualisations en mouvement et son expérience utilisateur. J'utilise les jeux vidéo comme plateforme de test, dans lesquels les visualisations en mouvement sont placées dans un arrière-plan chargé et dynamique mais doivent aider les joueurs à prendre des décisions rapides pour gagner. Mon étude montre qu'il existe des compromis entre la lisibilité de la visualisation en mouvement et son esthétique. Les participants recherchent un équilibre entre la lisibilité de la visualisation, l'adéquation esthétique au contexte, l'expérience d'immersion qu'apporte la visualisation, le support que la visualisation peut fournir pour gagner, et l'harmonie entre la conception des visualisations et leur contexte.

RÉSUMÉ ÉTENDU EN FRANÇAIS

Avec le développement des technologies informatiques, les visualisations ont quitté le papier pour s'afficher sur des supports interactifs, tels que les montres intelligentes, les téléphones mobiles et les tablettes. La mobilité et la flexibilité de ces appareils offrent des opportunités pour afficher des représentations de données à proximité de leurs référents de données et se déplacer avec eux. Par exemple, les données personnelles de santé et de fitness telles que la fréquence cardiaque, le nombre de pas et les informations liées au sommeil sont des types de données courants affichés sur le cadran des trackers de fitness [3], se déplaçant avec le référent de données (le porteur). Les utilisateurs de montres intelligentes peuvent vérifier ces données en levant leurs bras et en jetant un coup d'œil, que ce soit en restant assis, en marchant ou en faisant de l'exercice. Outre les données de suivi personnel, ces dernières années ont vu apparaître une gamme plus diversifiée de visualisations de données pouvant être en mouvement relatif par rapport au spectateur. Des exemples incluent les scores mis à jour en temps réel dans les sports (voir Table 1.1b), où les barres de score sont intégrées au-dessus de la tête des athlètes et se déplacent avec eux. Les spectateurs peuvent voir ces visualisations augmentées sur le grand écran dans le stade ou depuis leur télévision. Les joueurs de jeux vidéo peuvent voir des barres de santé mobiles attachées à leurs personnages dans les jeux vidéo (voir Table 1.1a) - les barres de santé se déplacent avec leurs personnages correspondants. Les joueurs doivent faire attention à ces barres de santé tout en accomplissant des tâches, telles qu'esquiver ou tirer, pour garder leur personnage en vie le plus longtemps possible. Pour naviguer dans les physicalisations, comme les visualisations imprimées sur la route (voir Table 1.1c, 1.1d), les spectateurs peuvent les lire en passant à côté. Les utilisateurs d'équipements portables peuvent lire sur leurs appareils en mouvement (voir Table 1.1e, 1.1f), comme lire les calories brûlées ou leur fréquence cardiaque en courant ou en merchant.

Dans tous les scénarios mentionnés ci-dessus, différents facteurs de mouvement, c'est-à-dire des facteurs qui caractérisent le mouvement, sont impliqués, tels que différentes vitesses, trajectoires et relations spatiales entre les spectateurs et les visualisations. Je nomme de telles visualisations visualizations in motion et les définis comme suit :

> *Visualizations in motion are visual data representations used in contexts that exhibit relative motion between a viewer and an entire visualization.*

Je commence cet abstract par l'introduction de *visualization in motion*. Ensuite, je présente le champ et les objectifs de ma recherche, j'expose mes questions de recherche ainsi que les approches méthodologiques, et je détaille mes contributions. Je termine ce chapitre par un bref aperçu de la structure de ma thèse.

Visualisation en Mouvement

Les facteurs de mouvement, qui sont des facteurs affectant ou décrivant le mouvement d'un objet, tels que la distance, la vitesse et le déplacement, jouent un rôle dans la communauté de la visualisation depuis longtemps, sous la forme d'animation. L'animation est fréquemment utilisée pour mettre en évidence des parties d'une visualisation, pour fournir des transitions fluides de points de données dans le temps [4–7], ou pour se transformer entre différentes représentations [8–12]. À l'inverse, *visualization in motion* concerne le mouvement relatif entre des *visualisations entières* et le spectateur.

Pour distinguer l'animation de *visualization in motion*, imaginez un nuage de points dynamique qui se met à jour en temps réel. Un simple point de données peut se déplacer d'une coordonnée à une autre en raison d'une mise à jour des données. Néanmoins, le mouvement de ce point de données se produit à l'intérieur du graphique. Le graphique entier ne change pas de position pendant ce processus. Un nuage de points deviendrait un *visualization in motion* si l'ensemble du nuage de points changeait de place, par exemple, sautait du coin supérieur gauche de l'écran vers le coin inférieur droit.

Cependant, *visualization in motion* ne concerne pas seulement les visualisations se déplaçant sur un écran. Outre les visualisations mobiles, *visualization in motion* implique également des cas où les spectateurs sont en mouvement. Imaginez que le nuage de points mentionné ci-dessus était un graphique 3D augmenté. Certains points de données pourraient en cacher d'autres lorsqu'ils sont vus sous différents angles. Un spectateur portant un affichage monté sur la tête pourrait avoir besoin de se déplacer pour les voir. Dans ce scénario, la visualisation (graphique 3D) ne change pas de position, tandis que le spectateur si. Une scène similaire se produirait si ce nuage de points était une physicalisation de données, c'est-à-dire un artefact physique dont la géométrie ou les propriétés matérielles encodent des données [13]. Les spectateurs dans le monde physique pourraient également devoir se déplacer pour voir l'ensemble du nuage de points physicalisé en raison du chevauchement de certaines parties sous différents angles de vue.

Maintenant, je décris un contexte possible d'où la source de données de ce nuage de points a été générée, lorsque la visualisation et le spectateur sont tous deux en mouvement. Une culturiste porte une montre intelligente pour surveiller sa fréquence cardiaque pendant son entraînement fonctionnel. Elle éteint l'application de moniteur sportif lorsqu'elle termine sa dernière série. Elle range son équipement et quitte la salle de sport. Sur son chemin vers la station de métro, elle se demande comment était la fonction de son cœur. Ainsi, elle clique sur l'étiquette de récupération sur sa montre intelligente et voit un nuage de points contenant un axe x du temps et un axe y du nombre de battements de cœur. Le nuage de points montre une tendance à la baisse de sa fréquence cardiaque dans les 3 minutes suivant la fin de son activité. Elle constate que son rythme cardiaque est passé de 127 à 97 battements par minute en 3 minutes. Cependant, elle remarque, à partir du nuage de points, qu'il y avait un pic à 2 minutes — sa fréquence cardiaque a légèrement augmenté. Elle veut connaître la raison, mais elle arrive à un carrefour sans feux de circulation. Elle baisse son bras, détourne son regard vers la circulation et termine son action d'apprentissage des données depuis sa montre intelligente en marchant. Dans son processus d'apprentissage des données, son bras bouge indépendamment et a un mouvement relatif avec ses yeux. Surtout lorsque son bras rebondit légèrement de haut en bas en marchant. *Visualization in motion* discute également de scénarios tels que celui-ci.

Considérant l'état de mouvement à la fois de la visualisation et du spectateur, je classe *visualization in motion* en 3 catégories[1] : (a) lorsque la visualisation est en mouvement tandis que le spectateur est statique, (b) lorsque le spectateur est en mouvement tandis que la visualisation reste statique, et (c) lorsque la visualisation et le spectateur sont tous deux en mouvement (Table 1.2).

Puisqu'il n'y a pas de mouvement relatif entre le spectateur et la visualisation lorsqu'ils sont statiques l'un par rapport à l'autre, je ne discute pas de la catégorie "Spectateur Stationnaire × Visualisation Stationnaire"

[1]Bien que les spectateurs statiques puissent également expérimenter un mouvement illusoire avec des visualisations stationnaires (par exemple, le mouvement stroboscopique ou le phénomène phi), nous excluons ce scénario car aucun mouvement relatif entre le spectateur et la visualisation n'est présent.

dans ma thèse. L'impact du mouvement relatif dépendra du type et de l'ampleur du mouvement relatif lui-même. Certains types de mouvement relatif, tels que les mouvements oculaires saccadiques ou les mouvements simples de la tête, ne conduiront probablement pas à un impact intéressant sur la lecture des visualisations, tandis que des amplitudes plus élevées de mouvement relatif conduiront à un impact plus mesurable, en fonction du scénario.

La définition de *visualization in motion* indique un espace de recherche beaucoup plus vaste que les scénarios précédemment décrits. Je me concentre sur ces trois catégories et les défis associés qui indiquent des directions de recherche possibles. Des illustrations de scénarios, des discussions sur les défis, ainsi que des travaux connexes peuvent être trouvés dans Chapter 2.

Portée de la Recherche

Mon contexte de recherche se situe dans le domaine de l'interaction homme-machine (IHM), contribuant spécifiquement à la communauté de la visualisation. Le sujet de ma thèse, *visualisation située en mouvement*, est une combinaison de visualisation située et de visualization in motion (Fig. 1.1).

Rogers *et al*. [14] ont défini l'Interaction Homme-Ordinateur (IHM) comme : "A multidisciplinary field that explores the design, evaluation, and improvement of interactive computing systems, focusing on the interactions between humans and computers.". Outre les ordinateurs traditionnels tels que les ordinateurs de bureau et les ordinateurs portables couramment utilisés dans la vie quotidienne, nous avons maintenant accès à l'informatique mobile sous forme de smartphones, de montres intelligentes et d'autres appareils mobiles et portables. En raison de la mobilité de ces appareils, les facteurs de mouvement doivent être pris en compte lors de l'étude des interactions entre les humains et les machines. Par exemple, les gens naviguent avec un smartphone en marchant, suivent leurs performances sportives depuis une montre intelligente, ou font des visites virtuelles avec un appareil monté sur la tête. De plus, avec le développement de la technologie informatique et la baisse des prix des composants électroniques, nous nous rapprochons de la vision de l'informatique ubiquitaire où les écrans d'information peuvent être placés et déplacés partout [15]. Un environnement d'informatique ubiquitaire offre des opportunités pour intégrer des représentations visuelles autour de nous dans le monde physique ou dans tout contexte nécessitant une visualisation d'informations. Les gens pourraient vivre dans un monde avec des représentations de données riches et visibles qui fournissent aux spectateurs des informations instantanées dans le contexte, sans avoir besoin de chercher ailleurs. Un scénario imaginé est : Eva se réveille le matin. Elle veut savoir si c'est le moment de recharger son compte d'énergie, elle traverse donc une matrice de données dans le salon, qui montre combien d'électricité et d'eau elle a consommées ce mois-ci et combien de services il lui reste dans son compte. Elle quitte la maison pour faire de l'exercice le matin. Il y a du soleil mais aussi des nuages dans le ciel. Elle aimerait connaître la météo pour le reste de la journée. Ainsi, elle change de direction et passe une autre route où elle apprend qu'une diffusion météorologique est affichée sur le sol. Après avoir vu la diffusion, elle veut vérifier à quelle distance elle se trouve de son objectif de course quotidien puisqu'elle a changé son itinéraire habituel de course. Comme tel, elle lève son bras et vérifie sa montre intelligente — elle a couru 62,5 Dans le scénario décrit, les relations de mouvement relatif entre Eva et les données visualisées sont diverses. Cependant, comment ces représentations de données visibles devraient être conçues, comment les intégrer avec leur référent de données pour mieux soutenir ces scénarios, et comment les gens peuvent percevoir des informations utiles à partir d'elles sont encore des questions de recherche ouvertes.

Dans le domaine de la visualisation, les chercheurs travaillent au développement de nouvelles représentations visuelles, de présentations et de techniques d'interaction pour amplifier la cognition humaine pour différents types de jeux de données, de tâches et de contextes d'application [16–19]. En particulier, les visualisations situées sont celles qui affichent des données à proximité des référents de données [20, 21]. Un référent de données est défini comme l'entité à laquelle les données se réfèrent. Selon la définition utilisée par Willett *et al*. [1], dans une visualisation de données située, les données sont directement visualisées près de l'espace physique, de l'objet ou de la personne auxquels elles se réfèrent. Un exemple simple de visualisation située est les étiquettes de prix dans un supermarché affichant des lignes d'historique de prix qui sont situées à proximité de leurs produits associés. Toute entité peut être un référent de données, y compris une personne, un objet virtuel et une chose physique. Les visualisations situées peuvent hériter de la propriété de mouvement de leurs référents de données — les visualisations peuvent devoir se déplacer avec les référents pour maintenir leur situéité. Ainsi, les visualisations situées peuvent se déplacer et doivent se déplacer dans certains cas (par exemple, l'analyse sportive augmentée Table 1.1b et les jeux vidéo Table 1.1a).

Comme je définis *visualization in motion* comme existant en présence d'un mouvement relatif entre le spectateur et la *visualisation entière*, *visualization in motion* peut être non-situé. Par exemple, pour avoir une vue complète d'un modèle 3D sur une page web interactive qui montre combien de catégories et quelle quantité de nourriture chaque pays asiatique et américain a exporté au cours des 50 dernières années, un spectateur restant chez lui en Europe pourrait avoir besoin de glisser, déplacer ou faire tourner le modèle de globe 3D à l'aide de la souris pour avoir une vue complète. Des scénarios similaires existent dans la réalité augmentée et virtuelle. Bien que dans mon travail, je discute des visualisations non situées en mouvement, mon principal focus est sur les visualisations situées en mouvement (Fig. 1.1), car de nombreux scénarios d'application existent déjà.

Questions et Objectifs de Recherche

J'espère établir *visualization in motion*, comme une direction de recherche émergente dans la communauté de la visualisation, car des explorations supplémentaires sont nécessaires pour informer la recherche sur la visualisation liée au mouvement. Avant de passer aux questions de recherche concrètes, je commence par définir les opportunités et les défis de recherche. De nombreuses questions de recherche doivent être répondues, telles que comment les facteurs de mouvement et spatiaux peuvent affecter la perception de la visualisation, comment concevoir visualization in motion, et comment intégrer visualization in motion dans des scénarios d'application réels. J'ai commencé ma recherche par la précision avec laquelle les gens peuvent lire visualization in motion. Les gens peuvent-ils obtenir des informations fiables à partir d'un graphique en mouvement ? Les vitesses de déplacement ou les trajectoires de mouvement affecteraient-elles la lisibilité, et dans quelle mesure ? Ensuite, j'ai ciblé la question de savoir comment concevoir une visualisation en mouvement. Cependant, cette question est trop large pour avoir une réponse unique. Pour affiner le sujet, des aspects supplémentaires devaient être pris en compte, tels que pour quels publics, dans quel contexte, et comment les visualisations en mouvement pourraient être personnalisées. Dans ma thèse, j'ai répondu aux questions de recherche suivantes :

1. Comment pouvons-nous définir *visualization in motion*? Quelles sont les opportunités et les défis de recherche de *visualization in motion*?

2. Comment les facteurs de mouvement affectent-ils la lisibilité de *visualization in motion* et dans quelle mesure?

3. Comment pouvons-nous intégrer et concevoir *visualization in motion* dans un scénario d'application réel?

4. Comment un contexte réel affecte-t-il la conception de *visualization in motion* et son expérience utilisateur?

Finalement, l'objectif de ma thèse est d'informer la conception de la visualisation située en mouvement en fournissant les premiers résultats fondamentaux de perception et un ensemble de considérations de conception.

Approche Méthodologique

Ma thèse s'appuie sur une phase d'analyse initiale, qui comprend une revue systématique de la littérature et des scénarios d'utilisation existants menant à un premier agenda de recherche de *visualization in motion*. L'agenda de recherche a conduit à plusieurs questions autour de la perception et de la conception de visualization in motion et, en tant que tel, a informé une série d'expériences de crowdsourcing contrôlées avec des analyses quantitatives pour comprendre l'impact de deux caractéristiques du mouvement (vitesse et trajectoire) que j'ai hypothétisées affecteraient la lisibilité de la visualisation. Basé sur les résultats de perception que les gens peuvent obtenir des informations fiables de visualization in motion, je passe ensuite à comprendre comment (a) intégrer et concevoir au mieux visualization in motion pour les contextes réels et (b) comment les contextes réels peuvent affecter la conception de visualization in motion et son expérience utilisateur. Pour répondre à ces deux questions, j'utilise un mélange de méthodologies, telles que des ateliers pour diverses conceptions de visualisation, une enquête pour comprendre les exigences des publics, un prototype de sonde technologique [2] pour le développement futur d'outils d'auteur, et des expériences de laboratoire avec analyse qualitative pour évaluer le processus de conception ainsi que la conception de visualization in motion. Les détails de ces phases sont décrits dans la suite.

- **Revue de Littérature :** Ma thèse a commencé par une revue de littérature approfondie et une collection complète d'exemples de scénarios existants impliquant des spectateurs en mouvement et/ou des représentations visuelles en mouvement, concernant non seulement la communauté de la visualisation mais aussi un éventail plus large de domaines d'application informatique, tels que l'analyse sportive, la vision par ordinateur et l'informatique ubiquitaire. Cela comprenait une large exploration de la littérature, des applications réelles et des scénarios fictifs. Les exemples recueillis à partir de mes classifications principales de visualization in motion peuvent être trouvés dans Chapter 2. Parallèlement, j'ai mené une revue de littérature des travaux précédents dans le domaine de la visualisation, de l'interaction homme-ordinateur et de la psychologie. Spécifiquement, je me concentre sur les caractéristiques du mouvement, y compris les vitesses, les trajectoires, la direction et l'accélération ; les relations spatiales entre spectateurs, visualisations et le monde ; la situéité, le contexte et la conception de visualization in motion; ainsi que les technologies pour réaliser visualization in motion. Sur la base de mon enquête, j'ai proposé un premier agenda de recherche indiquant les opportunités de recherche ainsi que les défis de recherche de visualization in motion. Les détails peuvent être trouvés dans Chapter 3.

- **Expériences de Crowdsourcing :** J'ai mené une série d'études de perception empiriques contrôlées sur une plateforme de crowdsourcing [22] pour enquêter sur la précision avec laquelle les gens peuvent lire les visualizations in motion. L'objectif était d'explorer si les facteurs de mouvement tels que les vitesses de déplacement et les trajectoires de mouvement affectent la lisibilité des visualizations in motion. Cette série d'expériences comprenait une introduction, un pré-questionnaire, un tutoriel, une étude principale incluant des essais d'entraînement et de test, et un post-questionnaire. D'autres chercheurs, y compris Heer *et al*. [23], Kong *et al*. [24], et Talbot *et al*. [25], ont mené des expériences de crowdsourcing contrôlées pour analyser la perception de graphiques simples, tels que les graphiques à bulles, les graphiques à barres et les treemaps. Pour analyser dans quelle mesure les vitesses de déplacement, les trajectoires de mouvement, ainsi que les représentations visuelles impactent la performance de lecture, j'ai effectué une analyse quantitative utilisant l'estimation par intervalle. Outre l'analyse quantitative, j'ai également utilisé une approche d'analyse qualitative pour enquêter sur les stratégies de lecture des participants. Spécifiquement, j'ai codé et classifié les réponses des participants aux questions ouvertes. La conception expérimentale concrète et l'analyse des données peuvent être trouvées dans Chapter 4.

- **Ateliers de Conception :** Dans la communauté de la visualisation, organiser un atelier de conception est une approche courante utilisée pour générer, diversifier et collecter de nouveaux designs de représentations visuelles. Des chercheurs en visualisation tels que Huron *et al*. [26, 27] et Willet *et al*. [28, 29] ont appliqué cette approche pour mener des activités de création et d'idéation. Dans ma thèse, j'ai organisé deux ateliers : un pour collecter des designs de visualization in motion avec de larges scénarios d'application et l'autre pour diversifier les designs de visualization in motion pour une application spécifique — la natation. Mes ateliers de conception étaient généralement organisés en trois phases : (a) introduction et explication de la tâche, (b) une session de conception accompagnée de présentations orales, et (c) une session de re-conception pour améliorer les designs précédents des participants. Les détails de chaque atelier de conception varient légèrement selon ses objectifs. Des descriptions détaillées pour chaque atelier peuvent être trouvées dans Section 2.2 et Chapter 6.

- **Enquête :** Les enquêtes peuvent aider à comprendre ce que les participants pensent des questions relatives à certains concepts [30]. De plus, les enquêtes peuvent être utilisées pour mesurer les souhaits, les habitudes et les coutumes des participants [31]. Pour assurer la validité écologique des visualisations appliquées dans le scénario d'application réel, j'ai mené une enquête en ligne avec des passionnés de natation pour explorer quelles données ils sont intéressés à voir visualisées lorsqu'ils regardent des courses de notation. L'enquête comprenait des questions démographiques et plusieurs groupes de questions dans lesquels les participants étaient invités à classer leur niveau d'intérêt pour chaque donnée. J'ai effectué une analyse quantitative en rapportant la distribution des niveaux d'intérêt par élément de données. Les détails de cette enquête peuvent être trouvés dans Chapter 6. Ma recherche comprend également des questionnaires plus courts. Par exemple, les pré-questionnaires de mes études utilisateurs comprenaient des questions démographiques, les questionnaires intermédiaires comprenaient des évaluations du niveau de confiance et les post-questionnaires comprenaient un classement des conditions liées à l'expérience. Ces questionnaires sont décrits en détail par étude dans Chapter 4, 5, et 6.

- **Prototypage :** Le prototypage est une méthode largement utilisée pour répondre à des questions de recherche spécifiques de manière appliquée, en particulier lorsque les questions de recherche proviennent d'un scénario d'application réel ou ont des publics cibles spécifiques, tels que des experts du domaine et le grand public. Des exemples incluent les Tree-Maps [32] — une technique de visualisation remplissant l'espace 2D qui représente des données hiérarchiques sous forme de rectangles imbriqués ; Charticulator [33] — un outil d'auteur qui permet de créer des dispositions de graphiques sur mesure et réutilisables ; et Vistylist [34] — un outil de support de conception qui permet le transfert du style visuel d'une visualisation picturale à une autre. Dans ma thèse, j'ai développé *SwimFlow* [35], une sonde technologique [2] qui permet aux concepteurs d'intégrer, de personnaliser et de prévisualiser en temps réel des visualisations en mouvement sur une vidéo jouable. *SwimFlow* combine les résultats analysés d'une enquête en ligne, des visualisations collectées lors d'un atelier de conception, une vidéo de natation en direct, ainsi que des contrôles fonctionnels et des panneaux de couches. Des descriptions supplémentaires de *SwimFlow* peuvent être trouvées dans Chapter 6.
- **Expériences en Laboratoire :** Au cours de ma thèse, j'ai mené deux études en laboratoire : une pour comprendre comment les facteurs contextuels affectent la conception des visualizations in motion et leur expérience utilisateur dans un contexte de jeu vidéo, et l'autre pour apprendre quelles difficultés et quels défis les concepteurs rencontrent lors de la conception des visualizations in motion. Les deux études comprenaient une explication de fond, un pré-questionnaire, un tutoriel, une étude principale composée d'essais d'entraînement et de test (un essai préparatoire et des sessions formelles pour la seconde), et un post-entretien. L'entretien postérieur comprenait un post-questionnaire avec des questions à choix fermés et une courte session d'entretien avec des questions ouvertes. J'ai principalement appliqué une analyse qualitative pour les deux études en rapportant la performance observée des participants et en codant les réponses aux questions ouvertes. J'ai également analysé quantitativement les questions à choix fermés en rapportant la moyenne, les intervalles de confiance à 95 % et la distribution.

Contributions

Ma thèse apporte les contributions suivantes :

1. Je définis visualization in motion et propose un premier agenda de recherche, incluant des opportunités de recherche et des défis pour la conception de visualizations in motion.
2. J'analyse les résultats d'une série d'études de perception en crowdsourcing pour répondre dans quelle mesure les gens peuvent lire précisément les informations provenant de visualizations in motion. Mes résultats montrent que la vitesse et la trajectoire ont un effet sur la lisibilité — des vitesses plus élevées et des trajectoires irrégulières conduisent à plus d'erreurs. Néanmoins, les gens peuvent obtenir des informations fiables de visualizations in motion.
3. J'étudie comment intégrer et concevoir visualization in motion dans un scénario d'application réel en développant une sonde technologique [2] pour permettre aux utilisateurs d'intégrer des visualisations

en mouvement dans le contexte d'une vidéo de natation et d'évaluer le processus de conception avec des designers professionnels. Mon étude utilisateur montre que les designers sont prêts et s'attendent à concevoir en contexte pour visualization in motion en prévisualisant immédiatement les effets de rendu du movement.

4. Je mène une étude utilisateur dans le contexte des jeux vidéo pour explorer l'impact du contexte sur la conception de visualizations in motion et leur expérience utilisateur dans un contexte de jeu vidéo. Mon analyse montre de nombreux compromis pour les considérations de conception qui devraient être pris en compte lors de la conception de visualizations in motion dans un contexte concret.

Aperçu Organisationnel

Après un chapitre introductif, le reste de la thèse est organisé en six chapitres. Le titre et une brève description de chaque chapitre sont les suivants :

- **Chapitre 2 Visualisation en Mouvement : Scénarios, Designs et Travaux Connexes** décrit trois classifications de *visualization in motion*, illustre des scénarios exemples par classification et passe en revue les travaux passés liés à la fois aux communautés de la visualisation et de la psychologie. Il présente également une collection d'exemples et un atelier de conception sur *visualization in motion* situé, ce qui conduit à un premier ensemble de considérations de conception.
- **Chapitre 3 Visualisation en Mouvement : Un Agenda de Recherche** présente *visualization in motion* comme un espace de recherche nécessitant une exploration plus approfondie, couvre un large éventail d'aspects à considérer lorsque des facteurs de mouvement sont impliqués dans la visualisation et esquisse un premier ensemble d'opportunités de recherche ainsi que de défis pour *visualization in motion*. Avec cet agenda de recherche, je propose *visualization in motion* comme un parapluie sous lequel l'impact du mouvement relatif sur l'expérience avec, et la perception de, visualisations peut être discuté et analysé.
- **Chapitre 4 Visualisation en Mouvement : Deux Évaluations sur l'Estimation Empirique de la Proportion de Magnitude** présente une série d'études de perception en crowdsourcing qui explorent la précision avec laquelle les gens peuvent lire des visualisations en mouvement, telles que des graphiques en anneau et des graphiques à barres se déplaçant à différentes vitesses et sous différentes trajectoires. Les résultats de ces études peuvent être vus comme une fondation de perception de base de mon travail suivant.
- **Chapitre 5 Concevoir la Visualisation en Mouvement : Intégration de la Visualisation dans une Vidéo de Natation** étudie comment concevoir des visualizations in motion situés dans un contexte de mouvement réel — la notation. J'ai d'abord mené une enquête en ligne avec des passionnés de natation pour analyser leurs besoins d'informations liées au mouvement. Ensuite, j'ai organisé un premier atelier de conception pour éliciter les défis de conception. Par la suite, j'ai développé une sonde technologique interactive [2] — *SwimFlow*, qui permet la création de visualizations in motion intégrés basés sur des données réelles dans une vidéo de natation. Huit designers ont évalué leur expérience de conception d'intégration de visualizations in motion par *SwimFlow*. L'analyse de cette évaluation

fournit un premier ensemble de considérations sur la manière dont un accès complet au contexte et aux effets de mouvement peut affecter le processus et les décisions de conception de visualizations in motion, et identifie des défis pour de futurs outils d'auteur complets pour la conception de *visualization in motion*.

- **Chapitre 6 Études de Visualisation Située en Mouvement dans le Contexte des Jeux Vidéo : Une Revue Systématique et une Évaluation** explore l'impact d'un contexte concret (jeux vidéo) sur la conception et l'expérience utilisateur des visualizations in motion. Une partie de ce travail provient d'une thèse de master que j'ai co-supervisée. Ainsi, je passe de "je" à "nous" dans la description suivante. Nous avons d'abord examiné systématiquement les visualizations in motion situées dans les jeux vidéo. Nous avons ensuite implémenté un jeu de tir à la première personne (FPS) — RobotLife, avec lequel nous avons mené une étude utilisateur avec des joueurs de jeux vidéo expérimentés. Nos résultats montrent comment les visualizations in motion peuvent affecter l'expérience utilisateur au-delà de la performance. Notre travail contribue à des considérations de conception sur les visualizations in motion, spécifiquement dans un contexte concret avec d'autres tâches primaires à accomplir (gagner le jeu) au-delà de la lecture de visualisation.
- **Chapitre 7 Travaux Futurs et Conclusion** fournit un résumé de ma thèse et des perspectives sur les travaux futurs possibles pour *visualization in motion*.

Contents

PUBLICATIONS

Journal articles

1. Lijie Yao, Anastasia Bezerianos, Romain Vuillemot, and Petra Isenberg. "Visualization in motion: A Research Agenda and Two Evaluation." In: *IEEE Transactions on Visualization and Computer Graphics* 28.10 (2022), pp.3546—-3562
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2. Lijie Yao, Romain Vuillemot, Anastasia Bezerianos, and Petra Isenberg. "Designing for Visualization in motion: Embedding Visualizations in Swimming Videos." *IEEE Transactions on Visualization and Computer Graphics*. In press.
   DOI: 10.1109/TVCG.2023.3341990, HAL: hal-04333890.

Under submission

3. Fairouz Grioui, Lijie Yao, Tanja Blascheck, and Petra Isenberg. "Reading Smartwatch Visualizations While Walking: Assessing Relative Motion Characteristics and Impact on Reading Performance" Under submission to: *ACM CHI Conference on Human Factors in Computing Systems, 14 September 2024.*

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8. Federica Bucchieri, Lijie Yao, and Petra Isenberg. "Situated Visualization in Motion for Video Games" In: *Posters of the European Conference on Visualization (EuroVis).*, Jun 2022, Rome, Italy.
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HAL: hal-03700418.

Under preparation

10. Lijie Yao, Federica Bucchieri, Victoria McArthur, Anastasia Bezerianos, and Petra Isenberg. "Situated Visualization in Motion Studied in the Context of Video Games: A Systematic Review and An Evaluation".

There is only one heroism in the world: to see the world as it is, and to love it.
— Romain Rolland (1866-1944)

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My thesis focuses on motion factors as well as their impact on the readability and design of visualization. Therefore, my first project was a series of perception studies to understand how motion factors affect readability. I am grateful for the suggestions on the visualizations' color selections that Dr. Steven Franconeri provided — it helped us to minimize the interference of irrelevant variables. Steven was also one of the jury members of my mid-term defense. He and Prof. Theophanis Tsandilas gave me significant comments on what I should do to complete the second half of my thesis.

After my mid-term examination, I continued working on visualizations in motion in real application scenarios. Sports analytics, which has rich, dynamic data and involves multiple motion factors such as speeds, trajectories, and direction, is a prevalent application domain. Thanks should also go to Dr. Romain Vuillemot. It is an honor for me to have an opportunity to collaborate with Romain, one of the earliest researchers focusing on sports analytics in the visualization community. Romain gave me a ton of support on sports tracking data, sports videos with copyright, and also on technical issues. Romain is super responsive and never misses our regular meetings. He always proposed in-depth insights and inspiration on interdisciplinary studies in order to connect our research questions with other domains. Romain's wide network with the French National Swimming Federation [36] and his efforts in sports video recording are extremely valuable. Without these, we could not proceed to our work on embedding visualizations in motion onto a live swimming video. Besides, I appreciate Romain for his kindness in introducing me and my work to other French colleagues — he invited me to give a talk on situated visualization in motion at IG-RV [37], Lyon, France, 2023. Specifically, I would like to thank our engineer, Mr. David Ludovic, who followed my work on SwimFlow [35] and has been completing it as an authoring tool.

Apart from sports analytics, video games are another promising application scenario that already carries moving visualizations, including health bars. I should thank my intern — Ms. Federica Bucchieri, who did her master's graduation internship with us as the developer of RobotLife [38] that we used in our evaluation of visualization in motion for video games. Federica put full motivation and passion into her work, completed her thesis with 100 percent effort, and made valuable contributions to our project. Additionally, I want to thank Dr. Mickaël Sereno, who supported us on a technical issue. Moreover, I have to express my appreciation to Dr. Victoria McArthur, who is an expert in the domain of designing video games.

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Last but not least, I appreciate my family and friends, who stand behind me, support me in heart and spirit, and talk with and listen to me. They are: my eloquent father, who always talks too much — Mr. Congbin Yao; my lovely mother — Ms. Yan Li; my Chinese friends, who are also fighting for their thesis — Ms. Liu Yang, Mr. Yuxuan Ding, Ms. Xiaoqiao Mu, and Mr. Xuanlong Yu; and my old friends, Ms. Mengting Chen and Mr. Zicheng Wang, who gave me a hand on proofreading of this dissertation.

During my doctoral study, I had a first-hand experience in scientific writing, teaching, and advising. I learned how to encourage myself and face criticisms and failures that can happen for any reason. I strengthened my abilities in coordination, communication, and collaboration and my skills in presentation and storytelling. It was a happy, fulfilling, and unforgettable time. I believe what I gained during my doctoral period will always benefit me.

1 - INTRODUCTION

With the development of computing technologies, visualizations have moved off paper and onto interactive media, such as smartwatches, mobile phones, and tablets. The mobility and flexibility of these devices bring opportunities to display data representations close to their data referents and move with them. For instance, personal health and fitness data such as heart rate, step counts, and sleep-related information are common data types displayed on the face of fitness trackers [3], moving with the data referent (the wearer). Smartwatch users can check these data by raising their arms and glancing, whether staying in a seat, walking, or exercising. Apart from personal tracking data, recent years have seen a more diverse range of data visualizations that can be in relative motion with respect to the viewer. Examples include real-time updating scores in sports (see Table 1.1b), where the score bars are embedded above the athletes' heads and move with the athletes. Audiences can see these augmented visualizations from the big screen in the stadium or from their TV. Video game players may see moving health bars attached to their characters in video games (see Table 1.1a) – the health bars move with their corresponding characters. Game players need to pay attention to these health bars while doing tasks, such as dodging or shooting, to keep their game character alive as long as possible. To navigate physicalizations, such as visualizations printed on the road (see Table 1.1c, 1.1d), viewers may read them while they are walking by. Users of wearable equipment may read from their devices when they are moving (see Table 1.1e, 1.1f), like reading calories burned or their heart rate while running or walking.

In all scenarios mentioned above, different motion factors, *i.e.*, factors that characterize motion, are involved, such as various speeds, trajectories, and spatial relationships between viewers and visualizations. I call visualizations such as these visualizations in motion and define them as follows:

> *Visualizations in motion are visual data representations used in contexts that exhibit relative motion between a viewer and an entire visualization.*

I start this chapter with the introduction of *visualization in motion*. Next, I present my research scope and goals, demonstrate my research questions as well as methodological approaches, and outline my contributions. I end this chapter with a brief overview of the structure of my dissertation.

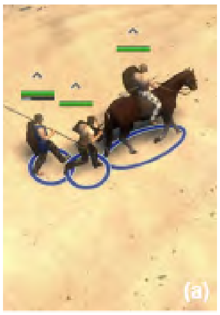
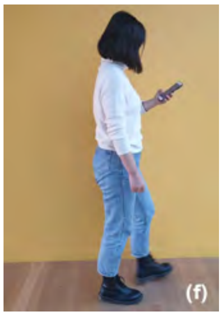
Categorization	Scenario 1	Scenario 2
Moving visualization & Stationary viewer		
Stationary visualization & Moving viewer		
Moving visualization & Moving viewer		

Table 1.1: Visualization scenarios that involve different types of relative movement between viewers and visualizations: (a) game characters in the game of *0 A.D.* [41] with attached health meters, (b) an augmented basketball match from the tool *Clipper CourtVision* [42], (c) a walkable visualization of the general organization of scholars at *ENAC* in France [43, 44], (d) an on-street bar chart that can be driven or walked by created by the *Respect New Haven* activist group, (e) a runner is looking at her fitness data, and (f) a person checking financial charts on her phone while walking to a meeting.

1.1 . Visualization in Motion

Motion factors, which are factors that affect or describe the movement of an object, such as distance, speed, and displacement, have played a role in the visualization community for a long time, in the form of animation. Animation is frequently used to highlight parts of a visualization, to provide smooth transitions of data points in time [4–7], or to morph between different representations [8–12]. Instead, *visualization in motion* is concerned with the relative movement between *entire* visualizations and the viewer. To distinguish animation from *visualization in motion*, imagine a dynamic scatter plot that updates in real-time. A simple data point may move from one coordinate to another due to a data update. Nevertheless, the movement of this data point happens inside the plot. The entire plot does not change its position during this process. A scatter plot would become a *visualization in motion* if the entire scatter plot changed its place, *e.g.*, jumped from the top-left corner of the screen to the bottom-right one.

Yet, *visualization in motion* is not only concerned with visualizations moving on a screen. Apart from moving visualizations, *visualization in motion* also involves cases where the viewers are in motion. Imagine the scatter plot mentioned above was an augmented 3D chart. Some data points could hide others when seen from different perspectives. A viewer wearing a head-mounted display might need to go around to see them. In this scenario, the visualization (3D plot) does not change its position, while the viewer does. A similar scene would happen if this scatter plot was a data physicalization, *i.e.*, a physical artifact whose geometry or material properties encode data [13]. Viewers in the physical world also might need to go around to see the whole physicalized scatter plot due to the overlapping of some parts between different viewing angles.

Now, I describe a possible context from which the data source of this scatter plot was generated, when both visualization and viewer are in motion. A bodybuilder wears a smartwatch to monitor her heart rate while doing functional training. She turns off the sports monitor application when she finishes her last set. She packs her equipment and leaves the gym. On her way to the subway station, she wonders how good her heart's function was. Thus, she clicks the recover label on her smartwatch and sees a scatter plot containing an x-axis of time and a y-axis of heartbeat counts. The scatter plot shows a tendency for her heart rate to decrease within 3 minutes after ending her activity. She finds that her heartbeat decreased from 127 to 97 times per minute within 3 minutes. However, she notices, from the scatter plot, that there was a peak at 2 minutes — her heart rate slightly increased. She wants to know the reason, but she arrives at an intersection without traffic lights. She puts her arm down, moves her sight over to the traffic, and ends her action of learning data from her smartwatch while walking. In her learning data process, her arm moves independently and has a relative motion with her eyes. Especially when her arm slightly bounces up and down while walking. *Visualization in motion* also discusses scenarios such as this.

Considering the movement status from both visualization and viewer, I classify *visualization in motion* into 3 categories[1]: (a) when visualization is in motion while the viewer is static, (b) when the viewer is moving while the visualization stays static, and (c) when both visualization and viewer are in motion (Table 1.2).

	Stationary viewer	Moving viewer
Stationary vis		×
Moving vis	×	×

Table 1.2: Classifications of *visualization in motion*

Since there is no relative motion between the viewer and the visualization when they are static to each other, I do not discuss the category "Stationary Viewer × Stationary visualization" in my thesis. The impact of relative motion will depend on the type and magnitude of the relative motion itself. Some types of relative motion, such as saccadic eye movements or simple head movements, will likely not lead to an interesting impact on reading visualizations, while higher magnitudes of relative motion will lead to a more measurable impact, depending on the scenario.

The definition of *visualization in motion* points to a research space that is much larger than the previously outlined scenarios. I focus on these three categories and associated challenges that point to possible research directions. Scenario illustrations, challenge discussions, as well as related work can be found in Chapter 2.

1.2 . Research Scope

My research context is in the human-computer interaction (HCI) domain, specifically contributing to the visualization community. My thesis topic *situated visualization in motion* is a combination of situated visualization and visualization in motion (Fig. 1.1).

Rogers *et al*. [14] defined Human-Computer Interaction (HCI) as: "A multidisciplinary field that explores the design, evaluation, and improvement of interactive computing systems, focusing on the interactions between humans and computers.". Besides the traditional computers such as desktops and laptops commonly used in daily life, we now have access to mobile computing in the form of smartphones, smartwatches, and other mobile and wearable devices. Due to the mobility of such devices, motion factors need to be considered when studying the interactions between humans and machines. For example, people navigate with a smartphone while walking, track their sports performance from a smartwatch, or take virtual

[1]While stationary viewers may also experience illusory motion with stationary visualizations (*e.g.*, stroboscopic motion or the phi phenomenon), we exclude this scenario as no relative motion between viewer and visualization is present.

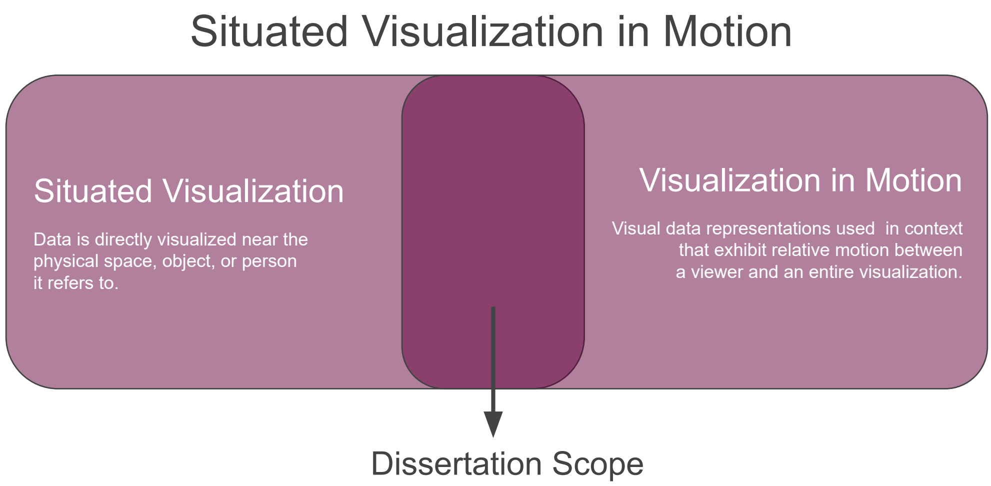


Figure 1.1: Research scope of the dissertation

tours with a head-mounted device. In addition, with the development of computing technology and the lower price of electronic components, we are coming closer to the vision of ubiquitous computing where information displays that can be placed and moved anywhere [15]. A ubiquitous computing environment offers opportunities to embed visual representations around us into the physical world or in any context that has an information visualization requirement. People could live in a world with rich, visible data representations that provide viewers with instantaneous information in the context, without the need to additionally search elsewhere. An imagined scenario is: Eva wakes up in the morning. She wants to know if it is time to charge her energy account, so she walks through a data matrix in the living room, which shows how much electricity and water she has consumed this month and how many utilities are left in her account. She leaves home to do morning exercise. There is sun but also clouds in the sky. She would like to know the weather for the rest of the day. Thus, she turns her direction and passes another road where she learns a weather broadcast is displayed on the ground. After seeing the broadcast, she wants to check how far away she is from her daily running goal since she changed her regular running itinerary. As such, she raises her arm and checks her smartwatch — she has run 62.5% of her setting distance and still has 1.2 kilometers to complete. She stops for rest and sees a bus pass in front of her with a virtual bar on the top showing how far to the next station. In the described scenario, the relative movement relationships between Eva and visualized data are diverse. However, how these visible data representations should be designed, how to integrate them with their data referent to best support these scenarios, and how people can perceive useful information from them are still open research questions.

In the field of visualization, researchers have been working toward developing new visual representations, presentations, and interaction techniques to amplify human cognition for different types of datasets, tasks, and application contexts [16–19].

Particularly, situated visualizations are those visualizations that display data in proximity to data referents [20, 21]. A data referent is defined as the entity that the data refers to. According to the definition used by Willett *et al*. [1], in a situated data visualization, the data is directly visualized near the physical space, object, or person it refers to. A simple example of situated visualization is price labels in a supermarket displaying price history lines that are located close to their related products. Any entity can be a data referent, including a person, a virtual object, and a physical thing. Situated visualizations can inherit the motion property from their data referents — visualizations may have to move with the referents to maintain their situatedness. As such, situated visualizations can move and have to move in some cases (*e.g.*, augmented sports analytics Table 1.1b and video games Table 1.1a).

As I define *visualization in motion* to exist in the presence of relative movement between the viewer and the *entire* visualization, *visualization in motion* can be non-situated. For example, to take a complete look at a 3D model through an interactive webpage that shows how many categories and how much food each Asian and American country has exported over the past 50 years, a viewer who stays in their home in Europe might need to drag, pan, or rotate the 3D globe model around by mouse to have a complete view. Similar scenarios exist in augmented and virtual reality. While in my work, I do discuss non-situated visualizations in motion, but my main focus is on situated visualizations in motion (Fig. 1.1), as many application scenarios already exist.

1.3 . Research Questions & Goals

I hope to establish *visualization in motion*, as an emerging research direction in the visualization community because further explorations are needed to inform motion-related visualization research. Before moving towards concrete research questions, I first outline research opportunities and research challenges. Many research questions need to be answered, such as how motion and spatial factors can impact visualization perception, how to design visualization in motion, and how to embed visualization in motion in real application scenarios. I started my research with how accurately people can read visualization in motion. Could people get reliable information from a moving chart? Would moving speeds or movement trajectories impact the readability, and to what extent? Then, I targeted the question of how to design visualization in motion. However, this question is too broad to have a single answer. To narrow down the topic, additional aspects had to be considered, such as for which audiences, under what context, and how the visualizations in motion could be customized. In my thesis, I answered the following research questions:

1. How can we define *visualization in motion*? What are the research opportunities and challenges of *visualization in motion*?

2. How do motion factors affect the readability of *visualization in motion* and to what extent?
3. How can we embed and design *visualization in motion* in a real application scenario?
4. How does a real-world context affect the design of *visualization in motion* and its user experience?

Ultimately, the goal of my thesis is to inform the design of situated visualization in motion by providing the first fundamental perception results and a set of design considerations.

1.4 . Methodological Approach

My thesis builds on an initial analysis phase, which includes a systematic review of the literature and existing use scenarios leading to a first research agenda of *visualization in motion*. The research agenda led to several questions around the perception and design of visualization in motion and, as such, informed a set of series of controlled crowdsourcing experiments with quantitative analyses to understand the impact of two motion characteristics (speed and trajectory) that I hypothesized would affect the readability of visualization. Based on the perception results that people can get reliable information from visualization in motion, I next move on to understand how to (a) best embed and design visualization in motion for real-world contexts and (b) how real-world contexts may affect the design of visualization in motion and its user experience. To answer these two questions, I use a mix of methodologies, such as workshops for diverse visualization designs, a survey to understand audiences' requirements, a prototype of technology probe [2] for future authoring tool development, and laboratory experiments with qualitative analysis to evaluate the design process as well as the design of visualization in motion. Details of these phases are described in the following.

- **Literature Review:** My thesis started with a thorough literature review and a comprehensive examples collection of existing scenarios involving moving viewers and/or moving visual representations regarding not only the visualization community but also a wider range of computing application domains, such as sports analytics, computer vision, and ubiquitous computing. This included a wide exploration of literature, real applications, and mock-up scenarios. The collected examples from my core classifications of visualization in motion can be found in Chapter 2. In parallel, I conducted a literature review of previous works from the domain of visualization, human-computer interaction, and psychology. Specifically, I focus on motion characteristics, including speeds, trajectories, direction, and acceleration; spatial relationships between viewers, visualizations, and the world; situatedness, context, and design of visualization in motion; as well as technologies to realize visualization in motion. Based on my investigation, I proposed a first research agenda indicating research opportunities as well as research challenges of visualization in motion. Details can be found in Chapter 3.

- **Crowdsourcing Experiments:** I conducted a series of controlled empirical perception studies on a crowdsourcing platform [22] to investigate how people can accurately read visualizations in motion. The goal was to explore if motion factors such as moving speeds and movement trajectories impact the readability of visualizations in motion. This series of experiments comprised a background introduction, a pre-questionnaire, a tutorial, a main study including training and test trials, and a post-questionnaire. Other researchers, including Heer *et al*. [23], Kong *et al*. [24], and Talbot *et al*. [25], have taken controlled crowdsourcing experiments to analyze simple chart perception, such as bubble charts, bar charts, and treemaps. To analyze to what extent the moving speeds, the movement trajectories, as well as visual representations impact the reading performance, I conducted a quantitative analysis using interval estimation. Apart from the quantitative analysis, I also used a qualitative analysis approach to investigate the participants' reading strategies. Specifically, I coded and classified the participants' answers to the open-ended questions. The concrete experiment design and data analysis can be found in Chapter 4.

- **Design Workshops:** In the visualization community, conducting a design workshop is a common approach used to generate, diversify, and collect new designs of visual representations. Visualization researchers such as Huron *et al*. [26, 27] and Willet *et al*. [28, 29] have applied this approach to conduct creation and ideation activities. In my thesis, I ran two workshops: one to collect visualization in motion designs with broad application scenarios and the other one to diversify designs of visualization in motion for a specific application — swimming. My design workshops were generally organized in three phases: (a) background introduction and task explanation, (b) a session of design accompanied by oral presentations, and (c) a re-design session to improve participants' previous designs. Details of each design workshop vary slightly according to its targets. Detailed descriptions for each workshop can be found in Section 2.2 and Chapter 6.

- **Survey:** Surveys can help to learn what participants think about issues pertaining to certain concepts [30]. Furthermore, surveys can be used to measure participants' wishes, habits, and customs [31]. To ensure the visualizations applied in the real application scenario are ecologically valid, I conducted an online survey with swimming enthusiasts to explore which data they are interested in seeing visualized when watching swimming races. The survey comprised demographic questions and several groups of questions in which participants were asked to rank their interest level for each data. I conducted a quantitative analysis by reporting the distribution of interesting levels per data item. Details of this survey can be found in Chapter 6. My research also contains smaller questionnaires. For example, pre-questionnaires for my user studies included demographic questions, middle-questionnaires included confidence level ratings, and post-questionnaires included experiment-related condition ranking. These questionnaires are described in detail per study in Chapter 4, 5, and 6.

- **Prototyping:** Prototyping is a widely used method to answer specific research questions in an applied way, especially when the research questions come from a real application scenario or have specific target audiences, such as domain experts and general audiences. Examples include Tree-Maps [32] — a 2D space-filling visualization technique that represents hierarchical data as nested rectangles; Charticulator [33] — an authoring tool that enables the creation of bespoke and reusable chart layouts; and Vistylist [34] — a design support tool that allows the transfer of the visual style of a pictorial visualization to another pictorial visualization. In my thesis, I developed *SwimFlow* [35], a technology probe [2] that allows designers to embed, customize, and preview visualizations in motion in real-time on a playable video. *SwimFlow* combines the analyzed results from an online survey, visualizations collected from a design workshop, a live swimming video, as well as functional controls and layer panels. Further descriptions of *SwimFlow* can be found in Chapter 6.

- **Laboratory Experiments:** During my thesis, I conducted two lab studies: one to understand how contextual factors affect the design of visualizations in motion and their user experience in a video game context, and the other one to learn what difficulties and challenges designers meet when designing visualizations in motion. Both studies comprised a background explanation, a pre-questionnaire, a tutorial, a main study composed of training and test trials (a trial-run and formal sessions for the second one), and a post-interview. The post-interview comprised a post-questionnaire including close-ended questions and a short interview session with open-ended questions. I mainly applied qualitative analysis for both studies by reporting participants' observed performance and coding open-ended questions' answers. I also quantitatively analyzed close-ended questions by reporting mean, 95% confidence intervals, and distribution.

1.5 . Contributions

My thesis makes the following contributions:

1. I define visualization in motion and propose a first research agenda, including research opportunities and challenges for designing visualizations in motion.

2. I analyze results from a series of crowdsourcing perception studies to answer to what extent people can accurately read information from visualizations in motion. My results show that speed and trajectory have an effect on readability — higher speeds and irregular trajectories lead to more errors. Nevertheless, people can get reliable information from visualizations in motion.

3. I study how to embed and design visualization in motion in a real application scenario by developing a technology probe [2] to allow users to embed visualizations under motion in the context of a swimming video and evaluate the design process with professional designers. My user study shows that designers are willing and expect to do in-context design for visualization in motion by immediately previewing the motion rendering effects.

4. I conduct a user study in the context of video games to explore the impact of context on the design of visualizations in motion and their user experience in a video game context. My analysis shows many trade-offs for design considerations that should be taken into account when designing visualizations in motion in a concrete context.

1.6 . Organizational Overview

After this introductory chapter, the remainder of the dissertation is organized into six chapters. The title and short descriptions of each chapter are as follows:

- **Chapter 2 Visualization in Motion: Scenarios, Designs, and Related Work** describes three classifications of *visualization in motion*, illustrates example scenarios per classification, and reviews related past work from both the visualization and psychology communities. It also presents an example collection and a design workshop on situated *visualization in motion*, which leads to a first set of design considerations.

- **Chapter 3 Visualization in Motion: A Research Agenda** presents *visualization in motion* as a research space that needs further exploration, covers a wide-ranging set of aspects to consider when motion factors are involved in visualization and outlines a first set of research opportunities as well as challenges for *visualization in motion*. With this research agenda, I propose *visualization in motion* as an umbrella under which the impact of relative motion on the experience with, and perception of, visualizations can be discussed and analyzed.

- **Chapter 4 Visualization in Motion: Two Evaluations on Empirical Magnitude Proportion Estimation** presents a series of crowdsourced perception studies that explore how accurately people can read visualizations in motion, such as donut charts and bar charts moving at different speeds and under different trajectories. The results of these studies can be seen as a basic perception foundation of my following work.

- **Chapter 5 Designing Visualization in Motion: Embedding Visualization in Swimming Video** investigates how to design situated visualizations in motion in a real motion context — swimming. I first conducted an online survey with swimming enthusiasts to analyze their motion-related information needs. Then, I carried out a first design workshop to elicit design challenges. Following, I developed an interactive technology probe [2] — *SwimFlow*, which allows the creation of embedded visualizations in motion based on real data onto a swimming video. Eight designers evaluated their design experience of embedding visualizations in motion by *SwimFlow*. The analysis of this evaluation provides a first set of considerations on how full access to the context and motion effects can affect the design process and decisions of visualizations in motion, and identifies challenges for future complete authoring tools for *visualization in motion* design.

- **Chapter 6 Situated Visualization in Motion Studies in the Context of Video Games: A Systematic Review and An Evaluation** explores the impact of a concrete context (video games) on the design and the user experience of visualizations in motion. A portion of this work comes from a master thesis that I co-supervised. Thus, I switch from "I" to "we" in the following description. We first systematically reviewed situated visualizations in motion in video games. We then implemented a first-person shooter (FPS) game — RobotLife, with which we conducted a user study with experienced video game players. Our results show how visualizations in motion can affect user experience beyond performance. Our work contributes to design considerations on visualizations in motion, specifically in a concrete context with other primary tasks to complete (win the game) beyond visualization reading.

- **Chapter 7 Future Work and Conclusion** provides a summary of my thesis and outlook on possible future work for *visualization in motion*.

2 - VISUALIZATION IN MOTION: SCENARIOS, DESIGNS, AND RELATED WORK

Visualizations in motion have not received much research attention, while animated visualizations have been studied more extensively. Work on animation has often focused on how to animate between different arrangements of data points [4, 7], changes in data (*e.g.*, graph) topologies or dimensions over time [5, 9]. Work on animation also explored how to zoom into data [6, 11], morph from one representation to another [8], and change viewing perspectives in 3D scenes [10, 12]. In general, work on animation in visualization is related to *visualization in motion* through the joint interest in motion. Yet, my focus is on **entire** visualizations exhibiting relative motion with the viewer. Real-world *visualizations in motion* have to often deal with additional complexities due to changing context conditions and unpredictable motion characteristics.

In this chapter, I first illustrate existing and promising *visualization in motion* application scenarios, as well as their related work. To elicit situated visualization in motion designs, I then present an online example collection and a first design workshop. From these work, I summarize a first set of design considerations for *visualization in motion*.

2.1 . Scenario Illustrations and Their Related Work

While *visualization in motion* as a research direction has not been systematically explored, past work exists in situations that involved relative motion between viewer and visualization. I focus on the scenarios where relative movement exists between the viewer and the visualization and associated challenges that point to possible research directions. The previous literature mentioned in this section relates to my work as a whole. The subsequent chapters (Chapter 4, 5, and 6) in this dissertation contain a dedicated related work section for each additional contribution.

2.1.1 . Moving Visualization & Stationary Viewer

In this scenario, stationary viewers see entire visualizations move. Viewers need to move their eyes and/or head to possibly track the visualization and to perceive the information that the visualization carries. The effort viewers put into reading a moving visualization depends on how accurately the viewers want to read the visualization, how complex the visualization is, and what kind of motion characteristics are involved. It is important to recall that my definition focuses on **entire** visualizations moving rather than data point animations or morphing, *i.e.*, where individual parts of visualization have different motion characteristics such as directions, trajectories, or speeds.

Figure 2.1: Examples of sports analytics contain situated visualizations under motion. (a) Bar charts accompany text close to the referent basketball players. (b) Bar charts and text labels are embedded over the heads of cyclists. (c) Text labels and figures follow behind the swimmers.
Image ©: Fig. 2.1 (a): SportBuzzBusiness [45]. Fig. 2.1 (b): created by Rouvy [46], released under the Creative Commons CC BY-SA license 🅭🅯🄎. Fig. 2.1 (c): published by CCTV-5 [47], released under the Creative Commons CC BY-SA license 🅭🅯🄎.

Moving visualizations for stationary viewers exist in sports analytics, where simple charts with single or multiple data points are attached to moving players or game equipment. For example, the potential shooting ratio bar close to each athlete in basketball (Fig. 2.1 (a)), the power-to-weight ratio[1] over the head of cyclists (Fig. 2.1 (b)), and the current speed of the three first swimmers (Fig. 2.1 (c)). Several companies (like Footovision [48] or SportsDynamics [49]) now commercialize tools that embed visualizations in videos (*e.g.*, Table 1.1b, Fig. 2.2). Such tools may be used by team coaches and players but also seen-by non-expert audiences during replays or debrief sessions on TV.

In contrast to these moving visualizations, several static sports visualizations have been developed in research as well. These tools add statistical analysis visualizations for sports such as table tennis [50–53], soccer [54–56], basketball [57–60], cycling [61], badminton [62, 63], or tennis [64]. Consistently, here, the visualizations are not in motion according to my definition; for example, VisCommentator [51] can, based on user selection, embed both static and animated visualizations in videos, but not visualizations in motion according to my definition. Motion is visible in cases where users can interact through zoom, pan, or rotation [55, 62, 64, 65], or when animated traces are replayed in the tools [52, 54, 56, 63]. However, in contrast to my work, previous literature did not discuss how to design moving visualizations and did not specifically focus on the impact of motion context on visualization design.

Video games are another domain that frequently involves moving visualizations. Some of them float in the air (*e.g.*, Fig. 2.3 (a)), some rest are attached to game entities (*e.g.*, Fig. 2.3 (b)), or even have been integrated into the design of

[1]Watts of cycling power produced per kilogram of cyclist's body weight

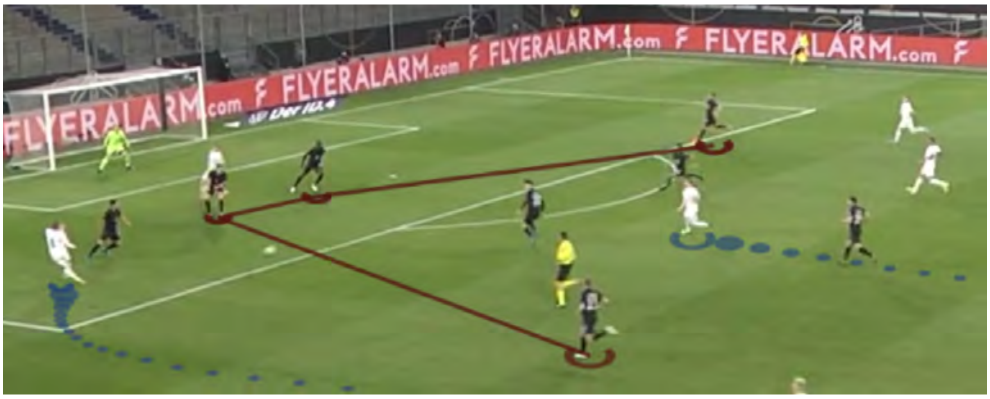


Figure 2.2: Examples of player video tracking for performance analysis. In this figure, the circle under each player's feet and its motion tail are individual representations of the player's current and past positions as well as his/her team membership.
Image ©: courtesy of Footovision [48].

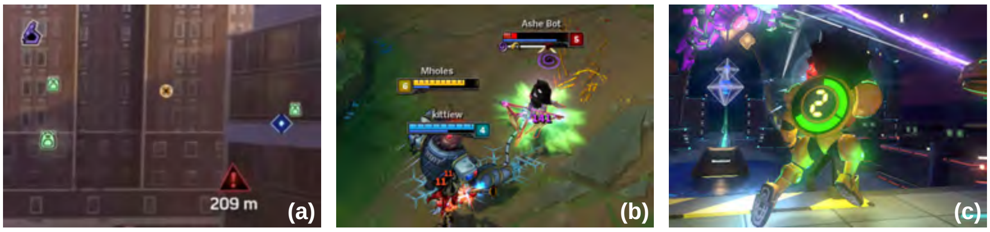


Figure 2.3: Examples of visualizations under motion in video games. (a) Iconic graphics float on the environment background. (b) Power and health bar charts are attached to the game characters. (c) A health donut chart is embedded into the design of the game character.

game characters (*e.g.*, Fig. 2.3 (c)). Compared to the display screen size, these visualizations moving in the game environment are small and carry simple data points. Visual encodings of such visualizations are diverse. Even for the same data item, the visual representations can be different. For example, the health value of a game character can be represented by a bar chart (Fig. 2.3 (b)) but also can be shown as a donut chart (Fig. 2.3 (c)).

Past work on game visualizations has mainly focused on the retrospective analysis of player cooperation and performance (*e.g.*, [66–68]). Real-time situated visualizations that move with characters often have the goal of providing situational information that helps players make quick decisions and perform and cooperate effectively. Bowman *et al*. defined a design space and proposed design patterns for visualization in games [69] but did not specifically discuss the design of visualizations in motion. Other previous works [70–72] from the design of video games focus on the impact of the game components on players' emotions and their gaming performance.

Figure 2.4: Examples of visual encoding used in object tracking. (a) A single uni-color rectangle to locate a Yo-Yo ball. (b) Multiple uni-color rectangles with text to annotate aircrafts. (c) Colorful rectangles with numbers to mark detected people.

Example game components include the game interface, game characters, and the design of the game background. The following work is closer to visualization in motion: Milam *et al*. [73] explored the effect of camera and object motion, but with a focus on visual load. Hicks *et al*. [71] investigated the impact of visual embellishments on player experience by using decorations attached to game entities, which did not carry any data. In contrast, no dedicated research investigated how the design of data-carrying visual encodings affects the gaming experience, especially under motion.

With the development of artificial intelligence, recognizing objects and labeling them in video frames has been the focus of object tracking (also called target tracking) [74]. The task of object tracking is largely partitioned into locating objects, maintaining objects' identities, and extracting their movement trajectories, and thus, object tracking generates rich data. The tracked objects can be pedestrians walking on the street [75, 76], vehicles moving on the road [77, 78], athletes running on the court [79–82], or animals such as fish [83]. In object tracking, the visual representations used to annotate tracking targets are mostly basic, such as simple rectangles (Fig. 2.4 (a)), sometimes with labels (Fig. 2.4 (b)) and/or a categorical color code (Fig. 2.4 (c)), that visualize the tracked objects' position, size, and potential type. While these are simple visualizations, with rising requirements such as automatic detection and annotation, visualizations in motion can be used in the future to embed more complex representations on tracked objects.

Finally, interaction more broadly can result in visualizations in motion when a user applies an interaction like panning, zooming, rotating, or changing viewing position to *entire* visualizations. In HCI, the impact of these operations has been studied for interactive user interfaces [85, 86], more specifically, in navigating maps [87]. However, reading visualizations during motion created by certain interactions may not always be a primary goal; for example, when a viewer scrolls a web page, embedded visualizations would typically be read before or after the scroll interaction. Nevertheless, a set of glyphs embedded on a map may be read during panning to identify locations with certain data characteristics.

2.1.2 . Stationary Visualization & Moving Viewer

In this scenario, a moving viewer focuses on a stationary visualization and experiences additional optical flow during self-motion in the world. Optical flow is the pattern of apparent motion of objects, surfaces, and edges in a visual scene caused by the relative motion between a viewer and a scene [88, 89].

A main consequence of viewer movement is a changing viewing angle and orientation towards the visualization. The effect of this type of motion has been researched sparsely in visualization, for example, in wall-sized displays, data physicalization, and AR/VR research. Past research has looked at moving viewers in front of wall-sized displays, for example as part of basic perception experiments [90], as input to change a visualization or its presentation—*e.g.*, through proxemic interaction [91–93] or hybrid images [94]—, or to visualize viewer movement [95]. Bezerianos and Isenberg's work [90] is most closely related. Their work showed no difference in the accuracy of moving participants and static ones standing far from the display wall when performing magnitude production trials on simple visual stimuli. However, participants who walked had better accuracy than those who stood close to the wall.

Similar impacts of view orientation exist in both physical and immersive spaces. A typical application scenario in a physical environment is physicalization, *i.e.*, a visualization can be represented in 3D as a physical object. The viewing angle one takes to look at a physicalization can affect occlusion — some parts of a physicalization may occlude others. In a previous study on how people approach and explore data physicalizations, Taher *et al*. [96] provided evidence that body movement is an important part of both data exploration and presentation. The authors pose further research questions regarding which movements lead to better insights or more accurate reading due to changes in viewpoints.

Promising application scenarios from immersive spaces include augmented reality (AR) and virtual reality (VR). Different from the physical world, a benefit of virtual 3D space is that people can attach visualizations to any referent. Thanks to head-mounted devices, previous research such as the work from Lin *et al*. [59, 97], which combined sports visualization and AR/VR, provided the possibility for users to move around and observe their previous basketball shooting trajectories in a 3D space.

2.1.3 . Moving Visualization & Moving Viewer

Both visualization and viewer might also move independently at the same time with relative motion between them. This motion can range from visualizations on smartwatches worn on the arm during a run (Table 1.1e) to larger changes in motion when visualizations are projected onto approaching traffic and seen from a moving vehicle.

A relevant research area for this scenario is mobile and wearable visualization (see also Chapter 3) as well as immersive analytics. Several previous studies on mobile phones have shown that walking increased workload and reduced performance in reading tasks [98–100] and the psychology literature has shown that walking in VR may negatively impact multi-object tracking [101]. As cognitive resources need to be similarly shared between navigation and reading data, it seems reasonable to expect similar negative effects for visualizations in motion. Several research efforts in VR have focused on the viewer's motion, such as examples illustrated in Locomotion Vault [102]. For example, research has shown that in a virtual environment, common motion effects such as walking can benefit the viewer's spatial memory [103]. However, understanding the impact of reading visualizations in motion still requires more dedicated work in VR and more broad immersive analytics research areas.

So far, research on wearable visualization has largely concentrated on smartwatches [104–106]. Much of the past work did not specifically design for or study moving observers. Exceptions include Schiewe *et al*.'s work [107] on visualizations for real-time feedback during running activities. Amini *et al*. [108] interviewed quantified-selfers about their in-situ data analysis activities and showed the variety of reasons people checked their fitness trackers during sports activities.

2.1.4 . Summary

According to my definition, *visualization in motion* already exists and has even been designed in practice in many research areas. Nevertheless, what research challenges and questions need to be further explored in *visualization in motion* and the dedicated investigation that can inform the perception and the design of visualization in motion are still missing. Also, the existing designs are still too fragmented to summarize design guidelines and toward design space. My work is to fill the gap by proposing a research agenda on *visualization in motion* and providing concrete results regarding perception and design considerations on *visualization in motion*.

2.2 . Designs in Practice

To more broadly investigate how visualization in motion has been currently designed in practice, applied in which scenarios, and attached to what data referent, I first conducted an online example exploration. After the example exploration, in order to elicit designs of situated visualizations in motion, I conducted an online hands-on design workshop with visualization practitioners.

This section is written mainly based on my original poster published at the *2020 IEEE Conference on Information Visualization [109].* The article was led by myself and co-authored with my supervisors: Anastasia Bezerianos and Petra Isenberg. In the following content, I switch from "I" to "we" to describe our work.

2.2.1 . Example Exploration

Procedure: We conducted our example exploration during the global pandemic. Thus, our investigation was based on an online search. We started our exploration by looking for animated or static images that involved motion factors, potential viewers, and promising data referents. We used a snowballing searching method. We first entered the keywords "moving", "movement", "visualizations", "viewer", and "in motion" in search engines. We then self-filtered the search results by finding examples that fit my definition of *visualization in motion* — include moving visualizations/viewers or can be mocked up to a promising scenario. Next, we checked the relevant content the search engines provided to see if they were useful. We noted the keywords the useful, relevant content additionally had and added these keywords for the next search. We repeated the search, self-filter, relevant content check, and keywords expansion process until we could not find more new examples. Through such a snowballing exploration, our search keywords expanded to augmented reality, virtual reality, mobile and wearable devices, ubiquitous settings, advanced mock-up techniques, as well as artifacts. To be able to review the examples later, we copied and pasted example images into a file and annotated each example by describing its application scenario, displayed data, data referent, and movement status of visualization/viewer.

Results: We collected 87 example images. Particularly, we found frequent examples of visualizations in motion in which visualizations were embedded on a moving data referent for a stationary viewer, such as instances in sports [110], visualizations of characters in online games, and augmented data annotation in a video. A few examples involved moving viewers and stationary visualizations —- the majority are physicalizations or AR application scenarios. Instances include the walkable data landscapes created by the British group of artists Stan's Cafe [111]. Advanced mock-up examples involved moving visualizations and moving viewers — they are the imagination of a combination of ubiquitous visualizations and mixed reality [112].

2.2.2 . Design Workshop

After our example collection, we found that although visualizations in motion have been realized in practice, dedicated design guidelines are still missing. To understand how people would design visualization in motion, which representations people would create, and what design difficulties are hidden, we conducted a first design workshop for visualization in motion.

Participants: Our 8 participants (2 ♀, 6 ♂) were members of our visualization research team. Of these, 3/8 were senior visualization researchers, and the remaining 5 participants were PhD/master students in visualization. The first author of this poster did not participate in the design workshop. Instead, she was the instructor.

Procedure: We asked participants to come up with situated visualizations in motion for three promising application scenarios: (a) an augmented soccer ball, (b)

Figure 2.5: Example designs for mobile visualizations created by participants in our workshop.

augmented shipping boxes moving on a conveyor belt, and (c) visualizations around an athlete for live sports tracking. Participants were asked to complete one design session per application scenario. In each design session, the workshop instructor first gave a 5-minute introduction of the background by playing videos of real scenarios, followed by a list of data that can be visualized under this scenario. Then, participants had 15 minutes to complete their design. After the design session, they were required to explain their design in an oral presentation. Participants were allowed to sketch on an online sketching board, on papers with pens, or on their tablets.

Results: We received 110 designs from our workshop. We saw a huge variety of designs, some of which are shown in Fig. 2.5. Participants used existing charts such as donut or pie charts, gauges, iconic representations such as speed lines, as well as simple text labels and graphic annotations we would not consider as data visualizations per se. Most visualizations were connected directly to the object of interest (ball, box, player), but some participants also augmented the ground/background.

2.2.3 . Design Considerations

From our online example exploration and design workshop collection, we collected 197 designs in total. We classified these 197 designs into 15 genres according to their representations, including donut charts, bar charts, pie charts, labels/text, icons, and heatmaps. Among these, by count, the most common were donut charts (34/197) and bar charts (23/197).

Based on our analysis and assessment of the drawn and existing examples, we formulated a first set of considerations for situated visualizations in motion that can serve as start questions to answer in more concrete further empirical testing:

Labels: Moving visualizations likely require a limited set of clearly readable labels as it might be difficult to focus and refocus on different words to read while in relative motion.

Unintrusive Design: Situated visualizations in motion are add-ons to objects of primary interest: data referents such as a soccer ball, an athlete, or a game character. As such, they should not take attention away from the object and blend well within the context of the referent. Visualizations directly overlayed on the object of interest might be considered too intrusive. At the same time, visualizations need to be visible enough to be clearly read.

Distance to Object of Interest: In order to establish a clear connection between data and referent, the situated visualization best stays close to the data referent and moves with it.

Simple Visualizations: Simple known visualizations should probably be preferred over more complex statistical graphics that would require scanning a large area or frequent comparisons with legends.

Simple Data: Datasets of a limited number of data points and dimensions might work better for situated visualizations in motion than more complex data.

2.3 . Summary

The results above show my initial investigations into the topic of situated visualizations in motion. Promising scenarios, as well as designs in practice, show that *visualization in motion* is a promising field of research that includes a large number of open research opportunities related to many other research domains. As such, I next propose a dedicated research agenda to outline what research questions *visualization in motion* contain and from where further exploration should start.

3 - VISUALIZATION IN MOTION: A RESEARCH AGENDA

As previously mentioned, there is still little work dedicated to the impact of motion and spatial factors on the perception and design of *visualization in motion*. The goal of this chapter is to point to **new possibilities for research on *visualization in motion*** and to show important factors that need more exploration. In this chapter, I summarize important future research in this space related to the scenarios introduced in Chapter 2. As Table 1.1 shows, visualizations in motion may be overlaid in 2D, may be physical, or shown in a 3D virtual world, which are drastically different viewing contexts with various types of motion. I, therefore, focus the **research agenda** on four broad themes: (a) the influence of different characteristics of motion, (b) the spatial relationship between the viewer(s) and the visualization(s), (c) future work on the situatedness of the visualization, and (d) technologies that can be used to realize *visualization in motion*.

Some aspects of these themes may be interrelated. It is not possible to provide distinct boundaries between themes. Rather, I focus on pointing out the base properties that may affect visualization reading and their research opportunities. Of course, combinations between aspects need to be further researched as well.

> This chapter is an updated version of the text from my original article published at *IEEE Transactions on Visualization and Computer Graphics [113].* The article was led by myself and co-authored with my supervisors and collaborator: Anastasia Bezerianos, Romain Vuillemot, and Petra Isenberg. In the following content, I switch from "I" to "we" to describe our work.

3.1 . Characteristics of Motion

In physics, motion is described as the phenomenon in which an object changes its position over time [114] according to a frame of reference. To research *visualizations in motion*, we, thus, first have to consider appropriate reference points. Taking the human viewer as the reference, a visualization can exhibit relative motion or relative immobility. If we consider a human viewer to be a fixed point of reference (even if the viewer is actually moving), relative motion exists if a visualization moves relative to this fixed viewer due to a different speed or motion trajectory. If both the human and the visualization do not move or move at the same speed along the same trajectory (*e.g.*, a human reading a stationary visualization on a moving airplane), there is no relative motion.

Central to our definition of *visualization in motion* is the existence of such relative motion of sufficient magnitude—beyond eye saccades or simple head movements that all human viewers would exhibit. In Chapter 2, we already discussed several research areas in which visualizations often need to be read under relative motion. The effects of relative motion for the viewer may involve changes in viewing angles, orientations, motion blurs, or changing visualization sizes, among others – all of which will be more or less pronounced depending on the characteristics of motion. Next, we list specific properties of motion that we expect might impact the effectiveness of moving visualizations but for which the gravity of the impact still needs to be empirically established. A main research challenge related to motion characteristics includes finding out how well people can track visualizations that are moving very fast and in unpredictable directions while, at the same time, the viewers need to read and understand the presented data.

3.1.1 . Speed

Definition: Speed determines how quickly the spatial relationship between the viewer and visualization changes.

Significance: In practice, many visualizations in motion may be attached close to their data referents and should move with them. Some of these embedded visualizations will move at high speed if their data referents move fast, for example, a speed gauge attached to a car driving on a highway. In contrast, some visualizations can move at a lower speed, such as the same gauge close to a walking person. We do not know if this gauge carrying a proportion moving at a fast speed can be read as accurately as the one moving at a lower speed. While we are not aware of studies in visualization that assessed speed for visualizations in motion, previous studies [115, 116] on dynamic text reading, indicate that text moving speed influenced reading comprehension. We expect effects on reading data visualizations as well, but their extent still needs to be evaluated.

3.1.2 . Trajectory

Definition: For visualizations in motion, the trajectory is the path along which the spatial relationship between the viewer and visualization changes.

Significance: Trajectories can be more or less regular and predictable and be embedded in a plane or 3D space. For example, trajectories can be the movement itinerary of a basketball player running on the court. This basketball player knows where they should go, and thus, their trajectory is predictable for themselves while unpredictable for another person. On the other hand, the basketball player's trajectory can be embedded on the floor of the court, which is in 2D. In contrast, it can also be visualized in 3D by considering jumps. We expect trajectory complexity to impact the accuracy of reading moving visualizations, and future studies should find ways to test simple trajectories (*e.g.*, during panning) and more complex ones (*e.g.*, during tracking of certain sports).

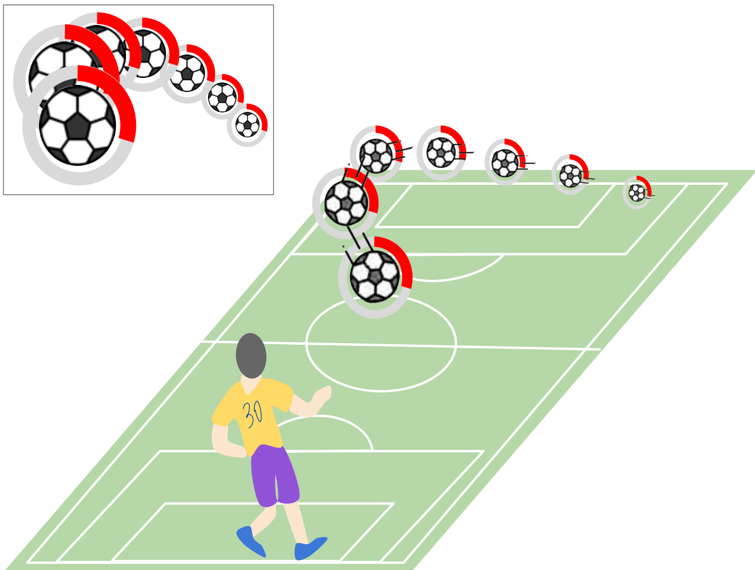


Figure 3.1: Changes to the perception of a soccer ball's size and position based on the distance between viewer and visualization.

3.1.3 . Acceleration

Definition: Acceleration describes the rate of change in speed.

Significance: In practice, the majority of the data referents will not move at a consistent speed — data referents can move faster, slower, or stop for a moment. Whether or not a visualization exhibits inconsistent speed depends on its data referent and the context its referent is in. For example, a running video game character with a current speed label should stop at a cross to wait for the traffic light. Although acceleration has not been extensively studied in the visualization community, previous research on animation still touched on changes in acceleration. Dragicevic *et al*. [117], for example, studied different types of pacing for animated transitions and recommended slow-in/slow-out transitions where objects begin to move slowly and then increase speed before decelerating when approaching the endpoint of the animation. The effect of acceleration, and in particular, unpredictable changes in speed, remains to be explored for visualizations in motion.

3.1.4 . Direction of Motion

Definition: Direction of motion refers to where in a reference space a visualization seems to be moving.

Significance: Direction is a motion characteristic that should be taken into account, especially when designing visualizations for a real application scenario — the movement direction of visualization should follow its data referent. For example, in a swimming race, a number label indicating a swimmer's current speed

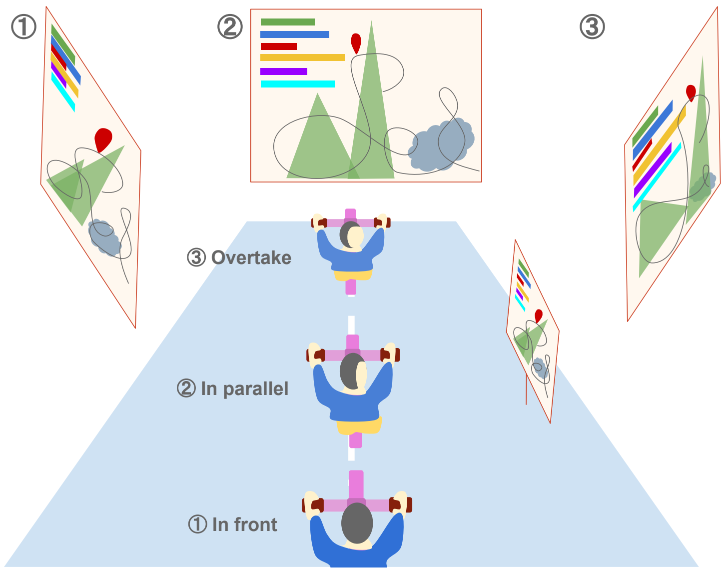


Figure 3.2: Changes of a moving cyclist's perception of a static map and bar chart based on changes between the viewer and the visualization space.

should follow the swimming direction and not in a verse direction. Nevertheless, the direction of motion has been little explored, even for animated visualizations. Indications for a possible effect might come from studies on reading direction. A past eye-tracking study [118], for example, indicated that reading direction has an influence on attention and memory. Other studies from psychology [119–122] also confirmed that reading direction affects text perception. How these effects transfer to reading visualizations should be further explored.

3.2 . Spatial Relationship Between Viewer and Visualization

Our next area for future research involves the spatial relationship properties to consider when designing visualizations in motion.

3.2.1 . Viewing Distance

Definition: Let us consider the viewing distance as the linear distance between the viewer and the visualization.

Significance: A change in viewing distance varies in how the visualization appears on the viewer's retina. Either a change in distance comes with a change in position on the retina and/or a change in visualization size. For example, look at Fig. 3.1, a visualization attached to a flying soccer ball would appear to change in size as the ball moves close to the viewer and might (unless the ball flies directly at the viewer) also appear to move through changes in position. How combined changes in visualization size and position would affect the viewers' data reading is still an open question.

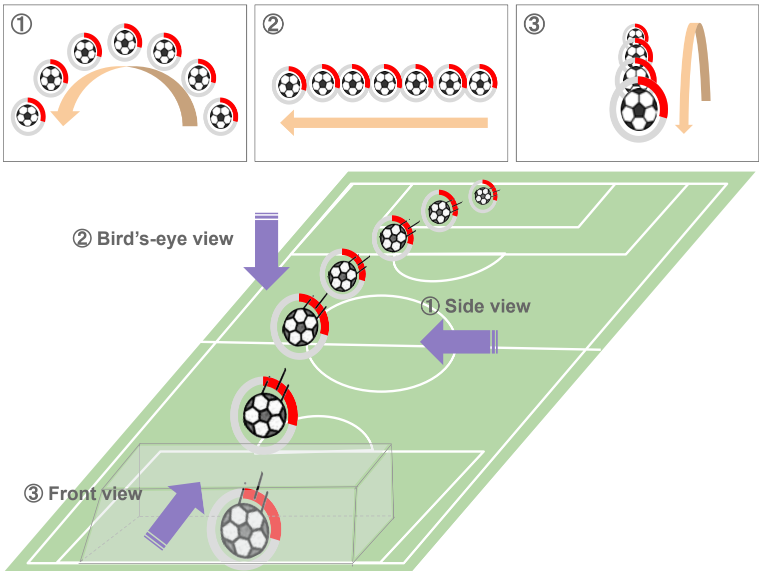


Figure 3.3: The same physical motion of a soccer ball will lead to different trajectories on the viewer's retina based on the relationship of the viewer to world space.

3.2.2 . Viewer vs. Visualization Space

Definition: A visualization has an inherent local coordinate system. Similarly, a viewer of this visualization can be modeled using a local coordinate system that changes with head and/or eye movement. The relationship of these two coordinate systems in a world impacts how a person sees a visualization in their field of view.

Significance: For example, in Fig. 3.2, a cyclist riding past a visualization on a static sign will see the visualization at different viewing angles as the visualization-to-viewer coordinate system transformation changes. When, instead, a viewer looks straight at a visualization that moves along their line of sight, the two coordinate systems stay aligned, and viewing angles will not change. In this case, motion effects will be seen through characteristics associated with changes in viewing distance. However, in most cases, the relationship between the two local coordinate systems will change over time when the viewer tracks a visualization in motion.

3.2.3 . Viewer vs. World Space

Definition: The world a visualization resides in can similarly be defined with a world-coordinate system. The relationship between the viewer's coordinate system and the world-coordinate system describes how the viewer looks at a specific scene.

Significance: For a single visualization in motion, the viewer-to-world space relationship will affect the perception of motion on the viewer's retina. Let's look at three kinds of canonical views: the front view, side view, and bird's-eye view. When a soccer game is broadcast, highlighted moments are often given a multi-angle, all-around camera replay. Fig. 3.3 shows how the same movement would be seen from the three different views. From the side view, the soccer ball with a situated donut moves from right to left in a beautiful arc. However, from the bird's-eye view, the movement seems to be linear. In the front view, not only is the trajectory changed from curved to linear movement, and the soccer moves up and down, but it is accompanied by a change in view distance as well – the soccer ball becomes bigger and bigger as it approaches.

Especially in scenarios with moving viewers and stationary visualizations, a main research challenge includes finding out how people experience and how effectively they read visualizations under changing viewing angles and potential inherent changes of visualization orientation.

3.3 . Situation, Context, and Design

In our exploration of visualizations in motion, we saw a wide variety of ways in which visualizations are displayed and related to the environment. In contrast to more standard data representations used for analysis in desktop environments, these visualizations were displayed with a large number of varying contextual factors and ways to connect to potential physical or virtual data referents [20]. The influence of factors such as the ones listed next requires further research attention:

3.3.1 . Autonomy of Motion

Definition: The autonomy of motion indicates who initiates and controls the visualization's movement — under or outside human control.

Significance: Depending on the situation and context of the visualization, the movement of a visualization may be outside human control (autonomous). This type of movement is widespread in natural environments, in flowing streams, falling leaves, swimming fish, *etc*. For example, an aquarium might add visualizations around swimming fish to represent their age, sex, or size. When the motion is non-autonomous, the movement is under the control of or influenceable by a human. For example, a player controls a moving character with an attached health bar in a video game. To what extent the autonomy of motion plays a role in how well visualizations can be tracked and read is still an open problem.

3.3.2 . Predictability of Motion

Definition: Predictability represents if the viewer can predict a movement — where the visualization would go at the next moment.

Significance: To a viewer, the relative motion of a visualization may be predictable or not. Predictable motion can come in the form of (a) motion with naturally predictable properties: for example, the movement trajectory of a swimmer in a swimming competition – each swimmer completes the race in their lane, and audiences understand that the swimmer's trajectory will be approximately linear; (b) movement under the control of the viewer: for example, when a viewer zooms, pans, rotates or scrolls a visualization, they can easily predict where the visualization will move. Unpredictable motion occurs when the movement does not have predictable properties because it does not follow natural motion paths. The same motion can be predictable for one viewer but unpredictable for another. For example, a soccer player can predict the ball's movement before kicking it, but for the audience, the ball's movement is unpredictable because it depends on the player's footwork. Previous research from neuroscience pointed out that viewers can better predict motion by tracking a moving target object [123]. However, their visual target was a Gaussian dot. We did not find any research explicitly stating that the predictability of motion positively or negatively influences visualization readability. Thus, it is still not possible to tell if the predictability of motion would impact a visualization's readability.

3.3.3 . Contextual Factors

Definition: Contextual factors are aspects of the context in which the visualization resides. These factors do not directly relate to the visualization but might have an impact on the perception of the visualization.

Significance: The scenarios outlined in Chapter 1 and 2 show a variety of contextual factors that can have an impact on how visualizations in motion are perceived. The examples involve visualizations on various backgrounds in scenarios that potentially involve noise or viewers with primary tasks such as riding a bike or fighting another game character. Especially when reading a visualization is not a primary task, visualization often cannot be focused on for longer periods of time. While researchers have studied the glanceability of smartwatch visualizations [104], the in-situ reading of data from visualizations will likely be impacted by application scenarios. For example, a wearer can easily read their heart rate from their smartwatch while running by raising their arm, but it will be difficult to raise an arm to read when swimming. Thus, how to design in-situ visualization in motion and how to let viewers efficiently perceive helpful information require design attention. Data physicalization scenarios also often include social challenges related to movement and contextual factors such as lighting or distractors like noise that might affect how people experience visualizations while moving. For example, a self-actuated bar chart depicts online poll replies with changing bar heights [124]. Where to place the chart is crucial at the design's outset due to the uncertain maximum bar space before the poll ends. As such, studying the impact of contextual factors on visualizations in motion will be important.

3.3.4 . Connection to Data Referents

Definition: Here, the connection indicates how close a visualization is to its data referent: not only from the physic space but also from the data relationship — does the data shown on the visualization come from its data referent, or is it related to its displayed context?

Significance: Willet *et al*. introduced data referents as (physical) entities and spaces to which data corresponds. We saw many examples of situated visualizations (according to the definition used by Willett *et al*. [1]) with varying degrees of connection between visualization and what the represented data referred to. Examples include visualization over or around game characters Table 1.1a, players in live sports tracking Table 1.1b, or fitness data shown on wearables Table 1.1e, include very close connections, while the data physicalizations in Table 1.1c and Table 1.1d show abstract data more broadly related to the place they are displayed in. Thanks to advances in technology, it is becoming easier to embed visualization in certain scenarios, such as live videos or on wearables that collect data in real-time related to specific locations or the wearer [125], and as such, there is a large design space to explore for embedded visualizations in motion.

3.3.5 . Visualization Design

Definition: Design parameters determine how a visual representation looks and can impact how it will be perceived.

Significance: There is ample evidence that visualization choice and design will impact the effectiveness and efficiency with which data can be read and understood without motion. These design choices also need to be studied specifically for visualizations in motion. For example, the representation type [126, 127], the visualization complexity [25, 128], the decoration of the representation [129–131], the size of the visualization [132], or its color selection [133, 134], may affect how people perceive a visualization in motion. Nevertheless, there is some limited past research in visualization that involved looking at the effects of motion. Researchers, for example, studied labeling and annotation in immersive analytics under motion and specifically factors such as viewing angle changes [135, 136] and spatial location changes [135, 137] of objects in the environment.

As such, there are limited dedicated design guidelines for people who already create visualizations in motion in practice. In our 2020 IEEE VIS poster (Section 2.2), we made first steps and collected design considerations from a set of 87 example images collected online, as well as 110 designs elicited during a design workshop. From these, we propose several visualization design characteristics to focus on for future research: the design of labels, the salience of the design, the distance to objects of interest, and the complexity of the design or shown data. In addition, several visualization in motion scenarios (object tracking, fitness tracking, sports analytics, . . .) involve dynamically updating data. It is still unclear how updates would be noticed and evaluated by viewers under relative motion.

3.4 . Technology

Many of the visualization in motion scenarios outlined in Chapter 2 depend on available technology such as wearables, AR/VR, or fabrication technology. Research on visualizations in motion can draw from and inspire available technology and can perhaps even shape future technologies. Here, we list a few technologies where research on visualizations in motion is particularly important.

3.4.1 . Stationary Screens

Examples: Stationary screens are very common in daily life. Examples include desktop monitors and wall-size displays.

Benefits: Seated viewers may experience visualizations in motion on any type of screen, such as those found in Table 1.1a and 1.1b. Despite the existing examples in games and sports analytics, we know relatively little about how visualizations moving across a screen are perceived by seated viewers. Exploring visualizations in motion for general screens can already have a large impact on growing and well-established industries and help improve how viewers experience data visualizations.

3.4.2 . Mobile and Wearable Devices

Examples: Various types of mobile and wearable devices exist, such as tablets, mobile phones, fitness trackers, and head-mounted devices.

Benefits: Mobile and wearable devices already carry visualizations in motion experienced by moving viewers, such as those shown in Table 1.1e and 1.1f. Smartwatches, in particular, are a growing market involving many wearers who aim to improve their health and well-being by tracking their data. Again, conducting research on how best to design visualizations under contextual factors such as the types of movement (running vs. walking), as well as lighting or primary tasks under which these devices are checked, is important.

3.4.3 . Physicalizations

Examples: Physicalizations are visualizations that encode data with physical entities. Examples include printable visualizations (in both 2D and 3D) and architectured visualizations.

Benefits: Data physicalizations can be constructed from a variety of materials and for a variety of purposes [138]. We mostly saw static physicalizations and moving viewers, such as those shown in Table 1.1c and 1.1d. For these scenarios, it would be interesting to explore physicalization properties and how they affect how moving viewers are able to experience the data. In these cases, in particular, the viewing distance and the spatial relationship between the viewer, physicalization, and the world would be changed with the viewer's movement. It might also be an interesting challenge for designers to come up with future moving physicalizations for static observers.

3.4.4 . Augmented Reality and Virtual Reality

Examples: Some of the AR, VR, and XR devices, such as AR glasses, can be considered mobile and wearable devices. Immersive techniques allow visualization practitioners to embed visual representations anywhere they want.

Benefits: visualizations in motion are particularly common in AR/VR scenarios as soon as viewers are free to move their viewpoints and positions in a 3D scene. One interesting opportunity for AR/VR is real-time visual feedback. Work from Wu *et al*. on VR table tennis skill training [65] and work from Lin *et al*. on AR visualization for basketball free-throw training [59] showed that real-time visual feedback could improve player performance. In some sense visualizations in motion in AR/VR share challenges with other scenarios, for example, when data representations can be moved around in a 3D scene (data physicalizations or flat screens) or when data is embedded with objects or devices (mobile and wearable devices). Many future projects on visualizations in motion in immersive analytics are open to be explored, in particular in relation to immersive experiences with data visualizations.

3.4.5 . Future Techniques

Examples: Here, we categorize all remaining technologies and/or devices that could possibly be used to realize visualization in motion in real application scenarios as future techniques that require further development to be readily usable.

Benefits: Apart from existing and known technologies that involve visualizations in motion, there are a number of future technologies for which visualizations in motion can help to produce promising application scenarios. Examples include visualizations to display on holographic projections, visualizations on or by drones, or visualizations embedded on robots [139]. Future technologies can help to build visualizations that are hybrids of data physicalization and digital representations in 3D spaces that could move autonomously (like robots) or can be flown (like drones). In these application scenarios, visualizations in motion could have become highly integrated into people's daily lives, providing a wealth of information to the viewer at all times. The representations could consist of smaller volumes of flexible visualizations. Understanding how the choice of technology may affect the perception of visualizations in motion remains an open research direction.

3.5 . Summary

My research agenda proposes a set of promising broad research directions for *visualization in motion*. As this topic will gain more importance in Visualization—especially with mobile, wearable, and immersive technologies evolving—new and updated challenges will emerge. In addition, delving into application scenarios will open up new research spaces with dedicated challenges and concrete research questions related to visualizations in motion. In particular, visualizations in AR/VR pose a rich and diverse set of motion-related challenges in the context of moving visualizations and moving viewers (see Section 2.1.3). My following experiments in Chapter 4 are most closely related to AR scenarios where 2D visualizations may be embedded in live video streams. However, the motion in 3D space of both viewers and visualizations in AR/VR pose challenges that stem from interaction, head movement, and/or locomotion that are interesting to tackle. However, as with real-world movement, we still do not know much about how human perception is affected when both viewer and visualization are moving in immersive scenarios.

In summary, visualizations in motion are still a wide-open research space. They include opportunities for design as well as for in-depth empirical research, as outlined above. Some inspiration and hypotheses for empirical studies can be derived from related work, but almost no work exists that has looked specifically at moving data representations. Besides fundamental research, many other research domains can benefit from visualizations in motion. For example, researchers in the computer vision area have developed advanced algorithms with high performance to detect and track objects. Their focuses are on how to improve algorithms' accuracy and how to reduce the latency without giving much attention to what information should be attached to the detected object and how to display data. In contrast, the exploration in visualizations in motion can bridge the gap between tracking data and information to display. Visualization in motion can also be applied to the design of mobile and wearable devices, especially to improve the user experience in different application scenarios. The design guidelines from empirical research in visualizations in motion can be used when selecting visual representations for motion context, such as sports tracking. Furthermore, visualizations in motion can be adapted to broad application scenarios by combining them with a vision of ubiquitous computing, such as the scenario illustrated in the film The Matrix as well as in Metaverse [112] — based on the using scenarios and the real data needs, information can be seen everywhere through visualizations.

4 - VISUALIZATIONS IN MOTION: TWO EVALUATIONS USING MAGNITUDE PROPORTION ESTIMATION

To address the lack of empirical work in the stationary viewer & moving visualization scenario, I began to study three aspects of my research agenda: two related to characteristics of motion together with a factor of visualization design. In particular, I wanted to understand **how accurately people can read *visualization in motion***. I chose to start with studying the effects of speed and trajectory complexity on representation type as I hypothesized that the readability of different representations could be highly influenced by these basic characteristics of motion. I conducted **two crowdsourced experiments**. In both experiments, I used a magnitude estimation task that required people to read a quantitative value from a proportion visualization, similar to tasks that would be required in my target domains — sports analytics (Chapter 5) and video games (Chapter 6).

As such, I tackled a first small portion of the research agenda. I assessed how speed and trajectory complexity affect the reading accuracy of two simple chart types and found that increasing speed and complexity of trajectories impacted participants' performance negatively but to different degrees. My results are promising first steps for future work towards an ultimate design space for *visualization in motion*.

> The following content is an updated version of my original article published at *IEEE Transactions on Visualization and Computer Graphics [113]*. The article was led by myself and co-authored with my supervisors and collaborator: Anastasia Bezerianos, Romain Vuillemot, and Petra Isenberg. In the following content, I switch from "I" to "we" to describe our work.

4.1 . Related Work

To complement the related work in Chapter 2, I present relevant past work related to our two crowdsourced magnitude estimation experiments.

4.1.1 . Dynamic Visual Acuity

Although motion relationships between viewers and visualizations have not been systematically explored in the visualization community, they have been discussed in psychological studies. The work most closely related to ours concerns dynamic visual acuity. Dynamic visual acuity (DVA) [140, 141] describes the ability of an observer to discriminate an object when there is relative motion between the observer and the object. In contrast to our work, the visual targets in DVA experiments are often

Landolt C, optotypes on Snellen chart, or strings of numbers. In DVA experiments, participants are generally asked to identify the orientation of optotypes or to read the numbers rather than reading magnitude proportions, as in our case.

Previous research on DVA [142–145], in which stationary participants were asked to identify the orientation of Landolt Cs moving at different angular velocities, found that with increasing velocity visual acuity decreased. Angular velocity is how fast an object rotates or revolves about an axis or at which the angular displacement between two bodies changes. Similar decreases in acuity were also found for moving participants judging stationary targets [146–148]. It remains unclear if these results also hold for more complex targets such as certain visualizations and more complex types of movements such as irregular trajectories.

4.1.2 . Magnitude Estimation

In our experiments, we tested how effective stationary viewers were at reading quantitative values from moving proportion visualizations (bar and donut charts) inspired by those seen in Table 1.1a and 1.1b. Our methodology involved a magnitude estimation experiment [128] performed on a crowdsourcing platform. The empirical magnitude proportion estimation is widely used in the visualization community with an aspect of perception. The earliest empirical estimation of magnitude proportion can be tracked to 1926 [149]. Eells asked students to make proportion estimations of sketched donut charts and bar charts. In the following hundred years, researchers such as Cleveland and McGill [128, 150], kept using similar magnitude estimation tasks to test the perception of visual representations. With the rise of crowdsourcing platforms, researchers started to run empirical magnitude estimations online. A representative crowdsourced study was conducted by Heer *et al*. [23] in 2010 — they validated the crowdsourcing graphical perception by comparing the results between lab-based and online studies with the same magnitude estimation tasks. Our study methodology differs slightly from previous work on crowdsourced perception experiments [23, 130, 131, 151–154] in that we paid particular attention to control the physical size (and speed) of the stimuli shown on participants' screens through a dedicated screen calibration step.

Previous work has compared the two general chart types we tested in static scenarios and under different variations. Blascheck *et al*.'s work [104] found that people were slightly faster at comparing two values in smartwatch-sized donut charts than in regular bar charts. The related work on pie charts vs. stacked bar charts found that often pie charts outperformed or were en par with stacked bars according to accuracy [149, 155, 156] but that stacked bar tasks were often completed more quickly [149, 156, 157]. Redmond [158] compared proportion visualizations similar to our experiments and used pies vs. a two-segment horizontal bar. Similar to past work, he found that pie segments were more accurately estimated than bar segments. Simkin & Hastie [157] also tested a proportion judgment task like ours and found that pie chart proportions judgments were more accurate than those on bar charts but took longer. In summary, the past body of work comparing pies to bar charts might predict a slightly better accuracy for donut charts.

4.2 . Studies on Visualization in Motion

Our choice for speeds, trajectories, and visualizations was motivated by common examples in sports or video games (Table 1.1a & 1.1b) where stationary viewers see visualizations of player or game performance move across the screen. As we are just beginning empirical investigations on visualizations in motion, we tested these simple motion characteristics in controlled settings to be able to isolate the effects of the tested motion characteristics more clearly. Next, we discuss the study design criteria shared by the experiments we conducted. We describe the design choices that differed in the individual experiment sections.

Documents and original experiment data can be accessed here:

- Experiment-Speed-Donut: https://osf.io/km3s2/,
- Experiment-Speed-Bar: https://osf.io/t748d/,
- Experiment-Trajectory-Donut/Bar: https://osf.io/9c4bz/.

The experiments' original code and code for the statistical analysis obtained a stamp of replicability, which can be found here:

- Visualization in Motion: A Research Agenda and Two Evaluations
  https://www.replicabilitystamp.org/index.html#https-gitlab-inria-fr-lyao-visinmotion

Following are links to online experiments as try versions:

- Experiment-Speed-Donut:
  https://motion.isenberg.cc/study1_speed_donut/index.php?PROLIFIC=False,
- Experiment-Speed-Bar:
  https://motion.isenberg.cc/study1_speed_bar/index.php?PROLIFIC=False,
- Experiment-Trajectory-Donut:
  https://motion.isenberg.cc/study2_trajectory_donut/index.php?PROLIFIC=False,
- Experiment-Trajectory-Donut:
  https://motion.isenberg.cc/study2_trajectory_bar/index.php?PROLIFIC=False.

All experiments were pre-registered:

- Experiment-Speed-Donut: https://osf.io/mjfn2,
- Experiment-Speed-Bar: https://osf.io/2st8r,
- Experiment-Trajectory-Donut/Bar: https://osf.io/rp3mx.

4.2.1 . Study Parameters and Variables

We assessed the readability of moving bars and donuts, showing proportions under two motion characteristics: speed and trajectory. To determine ecologically valid speed values and chart sizes, we analyzed a LaLiga 2019/2020 Barcelone 5-2 Mallorca soccer match [159] in full screen on a 27-inch 4K screen. We selected 100 random starting positions from a player kick and recorded both the physical and temporal start and end positions of the ball relative to the screen. From this

Table 4.1: All stimuli images (0%, 18%, 32%, 43%, 58%, 72%, and 83%) used in our experiments that, if printed without scaling, are shown at the size displayed on participants' screens.

Proportions	Donuts	Bars
0%		
18%		
32%		
43%		
58%		
72%		
83%		

data, we calculated the average physical speed of the soccer ball on the screen as an approximation using a linear trajectory between start and end points; and measured the average diameter of the soccer ball.

Choice of Visualization Representations: From our online example exploration and design workshop collection (Section 2.2), we collected 197 designs in total. We classified these 197 designs into 15 genres according to their representations, such as donut charts, bar charts, pie charts, labels/text, icons, and heatmaps. Among which, by count the most common were donut charts (34/197) and bar charts (23/197). Considering in practice the prevalence of the donut chart and the bar chart (see also Table 1.1 & Fig. 2.2), we chose donut and bar charts for our experiments.

The charts were drawn at the same physical size in cm for each participant. For Donut, we set the inner diameter to 0.75 cm and the outer diameter to 1 cm. This sizing would encircle soccer balls with a diameter of 0.5 cm on the screen, which was the most frequent soccer ball size according to our video analysis. We set the length of Bar equal to the average of the inner and outer perimeters of the Donut to ensure that the data resolution is the same, with a width of 0.25 cm (equaling to the thickness of Donut slice) and a length of 2.36 cm, see Table 4.1. In each chart, the target slice was colored in #E90738 and the other

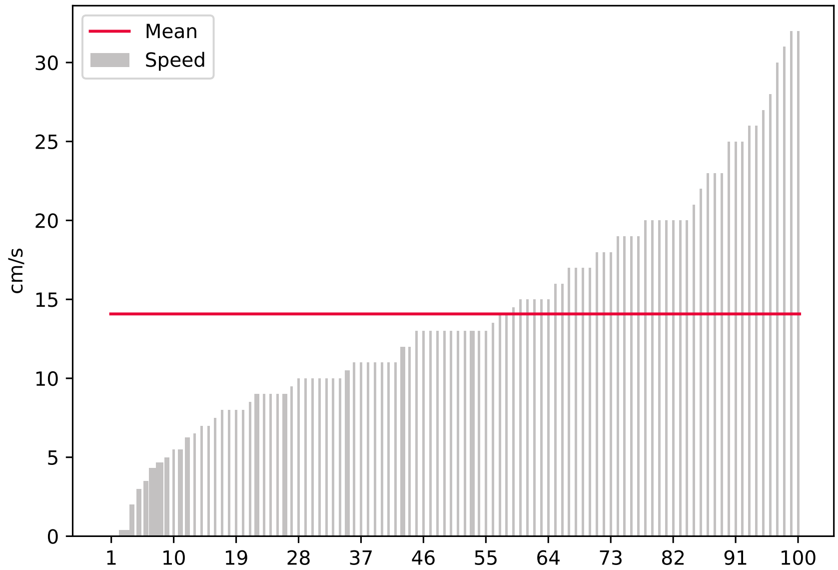


Figure 4.1: Average physical speeds in $\mathrm{cm/s}$ for 100 pairs of data points, sorted by speed. And the mean of these 100 data points. The width of every single bar represents the time taken between the soccer start and end position.

slice in #C3C1C1 to make the target warmer and higher chroma and reach an appropriate contrast ratio (4.61) with the white background.

Choice of Movement Speeds: The selected 100 pairs of start and end points included scenes with and without camera movement, hits and misses on goal, close-ups, and slow-motion replays. Among the 100 data pairs in our video analysis, the min speed was $0.4\,\mathrm{cm/s}$, the max speed $32\,\mathrm{cm/s}$, and the average speed $14.08\,\mathrm{cm/s}$ (Fig. 4.1). We then converted the highest, lowest, and average speed to the most popular screen sizes (Table 4.2).

From these measurements we chose our `Slow` speed to be $15\,\mathrm{cm/s}$ which is approximately the average speed for a 27-inch screen and the `Fast` speed as $30\,\mathrm{cm/s}$ which is approximately the fastest speed for 27-inch screens and the average speed on 65-inch TVs. In our speed experiments, we also included a `Static` condition as our baseline, in which the stimulus did not move on the screen. Each stimulus was shown on the screen for a fixed time of $1600\,\mathrm{ms}$, to ensure that we measured the impact of speed rather than stimulus exposure duration. Choosing $1600\,\mathrm{ms}$ allowed us to display one complete trajectory on our smallest accepted screen size in the experiment, given our `Slow` speed.

Table 4.2: Our recorded soccer speeds in $\mathrm{cm/s}$ converted to diverse screen sizes

Screen size	Highest speed	Lowest speed	Average speed
13-inch	15.41	0.19	6.78
14-inch	16.59	0.21	7.30
15-inch	17.78	0.22	7.82
16-inch	18.96	0.24	8.34
17-inch	20.15	0.25	8.87
22-inch	26.07	0.33	11.47
24-inch	28.44	0.36	12.52
27-inch	32.00	0.40	14.08
28-inch	33.19	0.41	14.06
32-inch	37.93	0.47	16.69
40-inch	47.41	0.59	20.86
43-inch	50.96	0.64	22.42
55-inch	65.19	0.81	28.68
65-inch	77.04	0.96	33.90
108-inch	128.00	1.60	56.32

Choice of Movement Trajectories: In our speed experiments, we wanted to isolate the impact of speed and chose a simple `Linear` — horizontal trajectory. In our trajectory experiments, we added `Irregular` trajectories. To extract ecologically valid irregular trajectories, we analyzed data from real 2018/2019 Premier League championship games. The data was provided by Footovision [48]—a performance analytic company—using state-of-the-art video tracking of players. We picked a typical game between Leeds United and Swansea and chose 7 trajectories of walking soccer players and 7 trajectories of running soccer players as seen from a birds-eye-view of the field using a custom visual analytics tool [160].

For each trajectory, we calculated 2 variations: a $180°$ clockwise rotation and a mirror on the y axis. We, thus, obtained 21 trajectories per speed (`Slow`, `Fast`). In our trajectory experiments, we therefore tested the following 4 conditions: `Slow` $\times$ `Linear` — condition and `Fast` $\times$ `Linear` — condition as we used in our speed experiment but play a role of baselines in the trajectory experiments, `Slow` $\times$ `Irregular` condition showing a slowly moving stimulus, and `Fast` $\times$ `Irregular` condition showing a fast moving stimulus. Images for all trajectories are available in the Section I.

Choice of Percentages: We based our choice of percentages to test on prior work. Cleveland & McGill's experiment [128] used 7 distinct proportions: 17.8%, 26.1%, 38.3%, 46.4%, 56.2%, 68.2%, and 82.5%. Using a similar methodology, Kong *et al*. [24] used four percentages (32%, 48%, 58%, and 72%) that account for participants' tendency to answer as factors of 5. We followed their choices but added additionally one smaller proportion and one larger proportion, leading to our analyzed proportions (Table 4.1): 18%, 32%, 43%, 58%, 72%, and 83%. We also added 0% as an attention check. For training trials, we used random percentages excluding the above 7 experimental proportions.

Dependent Variables: The key dependent variable analyzed in our studies was accuracy per trial which included the true error and absolute error of reading a specific proportion. We did not analyze answer time as a dependent variable, as the display time was fixed at $1600\,\mathrm{ms}$ to ensure we capture the effect of speed rather than stimulus exposure time. We also collected basic demographic information in a pre-questionnaire, including participants' experience with the type of chart shown (on a 10-point Likert item: 1 (novice) to 10 (expert)) and the frequency of playing video games or watching sports on TV (1 (never) to 10 (every day)). After each condition, participants rated the condition according to how confident they felt about the correctness of their answer on a 5-point Likert item (1 (not at all confident) to 5 (very confident)). At the end of the experiment, participants filled out a post-questionnaire and rated the difficulty of each condition they saw from 1 (not difficult at all) to 10 (very difficult).

4.2.2 . Experimental Software and Apparatus

Our experiments were conducted on Prolific [22]. In crowdsourced experiments, screens and pixel sizes may vary for each participant. While we could not control viewing distance from screens, we implemented a method to ensure at least the same physical display conditions. We controlled a) the movement speed in physical units of $\mathrm{cm/s}$ rather than $\mathrm{px/s}$ and b) the display size of the chart stimulus in cm instead of in px. Each participant went through a calibration phase where they held a bank-card-sized card (ISO/IEC 7810 ID-1 standard [161]) up to the screen and then adjusted a slider until a rectangle displayed on the screen matched the size of the physical card. From the calibration, we were able to infer a conversion ratio between px and cm for the screen of every single participant. This $\mathrm{px/cm}$ ratio was applied for drawing the stimuli, calculating the speed, and checking the participants' eligibility.

Our minimum screen size requirement to draw all stimuli was 13.3-inch in diagonal ($29.4\,\mathrm{cm}$ width). Participants who met this requirement and had completed the calibration phase were no longer allowed to adjust the page or window size.

At the beginning of each trial, we drew a focus area/point to show where the stimulus would first appear. After the display of the stimulus, we drew four masking images that flashed during a very brief amount of time ($80\,\mathrm{ms}$ in total [104] [162]). Then, participants typed their answers and submitted them by clicking a button.

4.2.3 . Procedure

Participants first agreed to an online consent form, followed by the screen calibration phase and the pre-questionnaire. Next, participants read through the experiment and task explanations and instructions and then completed blocks of trials. After completing the trials, participants filled out the post-questionnaire. At the end of each session, participants optionally described their strategies and gave comments.

The experimental trials were grouped in several blocks depending on the number of conditions. In the speed experiments, there were three speed conditions (`Static` ▶, `Slow` ⏩, `Fast` ⏩), resulting in 3 blocks of trials. In contrast, the trajectory experiments had 4 blocks since there were 4 speed × trajectory conditions (`Slow` ⏩ × `Linear` —, `Fast` ⏩ × `Linear` —, `Slow` ⏩ × `Irregular`, `Fast` ⏩ × `Irregular`). The condition order was randomized per participant using a Latin square.

Each block was composed of training and experimental trials. In a trial, participants had to estimate in whole numbers the proportion displayed in red. To proceed to the experimental trials, participants had to correctly answer 6 training trials. For each training trial, we accepted as correct any answer in the range of ± 10 percentage points. We displayed feedback about their entered answer, the exact proportion, and their progress in the training. During the experimental trials, we did not provide feedback on correctness.

Each block of experimental trials consisted of 21 trials (7 proportions in a random order per participant × 3 repetitions). We asked participants to make a quick estimate. After each block, participants rated their confidence in the current condition.

We had 3 attention trials per block of experiment trials. These were trials where the proportion was set to 0% and were easy to spot. As the speed experiments had 3 blocks, they included 9 such attention trials, and the trajectory experiments included 12 such trials in its 4 blocks. Our acceptable range for participants' given answers to these attention check trials was 0–10 percentage points. Thus, we terminated the experiment for participants who failed 6 attention trials in the speed experiments and 8 in the trajectory experiments. Participants were told clearly in the instructions that the experiment included attention trials and that failure to do them correctly would result in the session to not be completed and paid.

We conducted two speed experiments: one on `Donut` and one `Bar` — with 60 participants each × 3 blocks (3 conditions) × 21 trials per block = 3780 trials per experiment. Similarly, there were two trajectory experiments, one per chart type with 60 participants each × 4 blocks (4 conditions) × 21 trials per block = 5040 trials per experiment. The 21 `Irregular` trajectories for `Slow` ⏩ speed and another 21 `Irregular` trajectories for `Fast` ⏩ speed were shown in a random order per participant.

4.2.4 . Analysis Approach

We conducted our data analysis only with complete answers. All incomplete answers or the answers from participants who did not finish their experiment sessions for any reason were excluded. We used interval estimation [163] to interpret our results: we report sample means and 95% confidence intervals (CIs). We used BCa bootstrapping to construct confidence intervals (10,000 iterations) to compare chart movement speeds in the speed experiments and speeds × trajectories. The CIs of mean differences were adjusted for multiple comparisons with Bonferroni correction [164]. To compare Donut and Bar we used bootstrap confidence interval calculations for two independent samples. We drew inferences from the graphically-reported point estimates, and interval estimates [165]: when reading a CI of mean differences, a CI that does not overlap with 0 provides evidence of a difference, which corresponds to statistically significant results in traditional p-value tests. Nonetheless, CIs allow for more subtle interpretations. The farther from 0 and the tighter the CI is, the stronger the evidence. No significance test was performed, but equivalent *p*-values can be obtained from CI results following Krzywinski and Altman [166]. We also report the mean absolute error per proportion for each condition.

4.2.5 . Participants

Per experiment, we recruited 60 valid participants whose approval rate was above 95%; participants could only take part in one of the experiments as per our experiment settings. All participants had normal or corrected-to-normal vision and reported having no color vision deficiency. We report the composition of participants and their remuneration separately in the section for each experiment.

4.3 . Experiment-Speed (Donut/Bar) Results: The Effect of Speed on reading accuracy

The 60 participants involved in Donut (24 ♀, 35 ♂, 1 unspecified; 19 students) had an average age of 23.45 years (*SD* = 5.36). Participants' familiarity with donut charts was *M* = 6.10/10, *SD* = 2.50 and their frequency of watching soccer matches on TV or play video games was *M* = 4.66/10, *SD* = 3.07. The 60 participants involved in Bar (23 ♀, 37 ♂; 44 students) had an average age of 24.58 years (*SD* = 5.85). Participants rated their familiarity with bar charts as *M* = 6.45/10, *SD* = 2.45) and their frequency of watching soccer matches on TV or playing video games as *M* = 6.65/10, *SD* = 3.03.

Since our two experiments on speed (Donut, Bar) were conducted separately, the remuneration was a little different. The average completion time for Donut was 17.55 min. Based on an earlier pilot (average completion time was 12 min), we set the remuneration to £1.80. Given the longer actual duration, we improved our remuneration accordingly for the second experiment (Bar). The

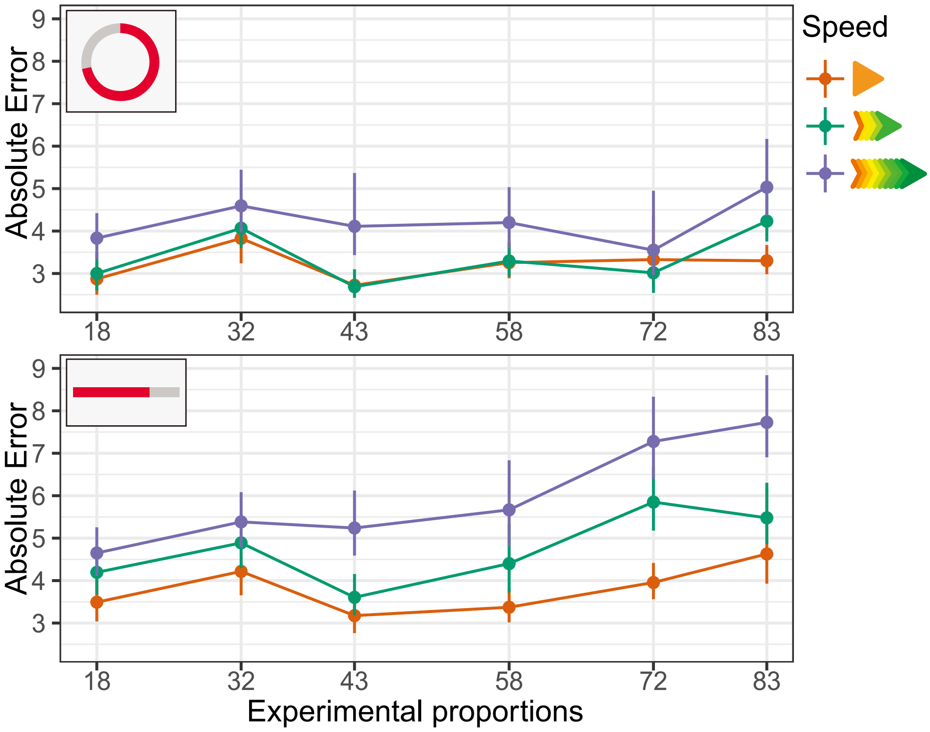


Figure 4.2: Experiment-Speed absolute error results for `Donut` (top) and `Bar` (bottom) per proportion.

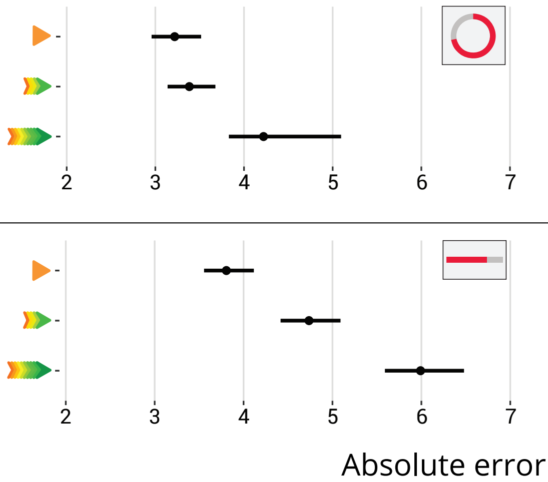
average time taken to complete the `Bar` experiment was 17.46 min, and each participant was paid £2.55.

4.3.1 . Speed per Representation

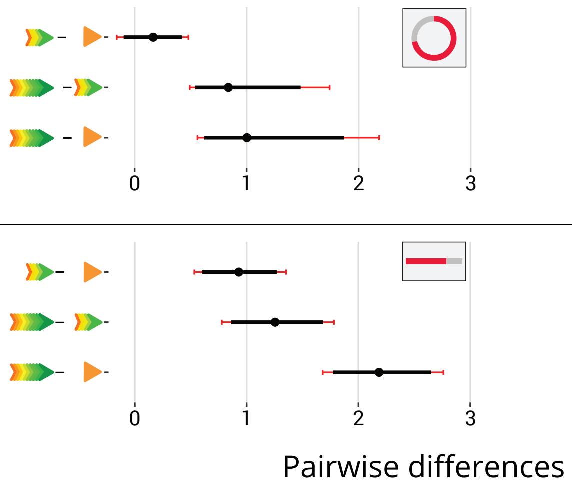
Table 4.3 shows the participants' mean absolute error per speed, the pairwise differences in absolute error across two speeds per chart type, and the differences across two representations. Fig. 4.2 includes the absolute errors split by proportion per speed and chart type.

Speeds: We can see from Table 4.3: Top, that high speeds did have an influence on human readability. Looking at the pairwise differences (Table 4.3: Middle), we see evidence that `Fast` speed caused more errors than `Static` and `Slow` speed conditions in both `Donut` and `Bar` representations in the respective experiments. But for both chart types in practice the differences were small, around 1–2 percentage points. For `Donut`, we have no strong evidence for a difference between `Slow` speed and baseline (`Static`): participants' average performance on `Slow` speed was similar to the baseline (`Static`). However, for `Bar`, participants' average performance was clearly better on `Static` conditions than on `Slow` ones.

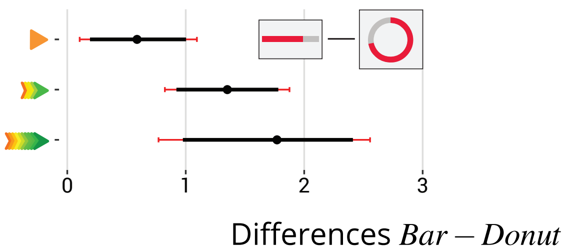
Table 4.3: *Absolute error* analysis for Experiment-Speed. Top: Average mean absolute error in percentage points for each chart type. Middle: Pairwise comparisons for each speed and representation. Bottom: Differences of mean absolute error across representations. Error bars represent 95% Bootstrap confidence intervals (CIs) in black, adjusted for pairwise comparisons with Bonferroni correction (in red).



3.22	[2.96, 3.52]
3.38	[3.14, 3.68]
4.22	[3.83, 5.10]
3.81	[3.56, 4.12]
4.74	[4.42, 5.09]
5.99	[5.59, 6.48]



0.17	[-0.10, 0.42]
0.84	[0.54, 1.48]
1.00	[0.62, 1.87]
0.93	[0.60, 1.27]
1.25	[0.86, 1.68]
2.18	[1.77, 2.65]



0.59	[0.19, 1.00]
1.35	[0.92, 1.78]
1.771	[0.98, 2.41]

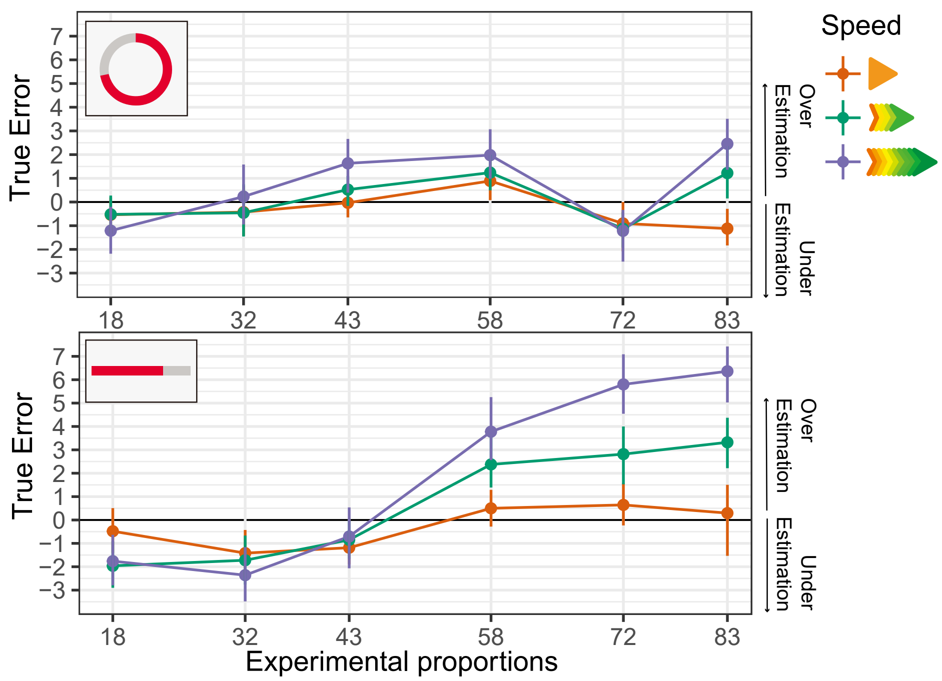


Figure 4.3: Experiment-Speed true error results for Donut (top) and Bar (bottom) per proportion.

Proportions: When looking at absolute errors per proportion for Bar (Fig. 4.2: Bottom), we see that participants' absolute errors tended to be higher with increased speed for all proportions. There may also be a tendency for error to increase in larger proportions. For Donut, (Fig. 4.2: Top), similarly, participants on average made more errors with Fast speed for all proportions. But absolute errors were similar in the Slow speed and Static condition across proportions with the exception of the 83% proportion.

When looking at true errors (Fig. 4.3: bottom) of specific proportions we have interesting tendencies for Bar. For proportions less than 50%, participants tended to make smaller estimates (underestimate), while for proportions greater than 50%, participants tended to make larger estimates (overestimate). As the speed and proportion increased, the degree of estimation bias increased - getting further away from the exact answer, with the exception of the 43% proportion. For Donut true errors (Fig. 4.3: top), the tendencies are less clear. For a few proportions (18% and 72% for all speeds, 32% for Static and Slow) participants underestimated, whereas for the rest, they overestimated. The estimation bias with Donut became larger as the speed increased, but there was no indication that the estimation bias became larger as the proportions increased, with the exception of the 83% proportion.

Table 4.4: Experiment-Speed: Confidence in the correctness of responses per speed and chart type with median (MED), average (AVG) and standard deviation (SD). 1: Not at all confident, 5: Very confident.

		1	2	3	4	5	MED	AVG	SD
Static	Donut	0	2	9	34	15	4	4.03	0.74
	Bar	0	1	12	31	16	4	4.03	0.74
Slow	Donut	0	0	13	38	9	4	3.93	0.61
	Bar	0	4	15	32	9	4	3.77	0.79
Fast	Donut	0	4	19	30	7	4	3.67	0.77
	Bar	1	5	19	26	9	4	3.62	0.90

Table 4.5: Experiment-Speed: Difficulty rating per speed and per chart type with median (MED), average (AVG) and standard deviation (SD). 1: Not at all difficult, 10: Very difficult.

		1	2	3	4	5	6	7	8	9	10	MED	AVG	SD
Static	Donut	21	18	9	2	2	3	3	1	1	0	2	2.63	2.02
	Bar	22	21	7	3	1	2	2	1	1	0	2	2.42	1.87
Slow	Donut	6	11	15	9	8	7	1	1	2	0	3	3.73	1.93
	Bar	6	11	13	16	8	4	1	1	0	0	3.5	3.50	1.57
Fast	Donut	1	3	7	8	7	4	7	13	6	4	6.5	6.10	2.44
	Bar	3	3	3	8	8	9	10	8	6	2	6	5.87	2.32

4.3.2 . Speed across Representation

Table 4.3: Bottom shows the differences between Bar [Bar] and Donut [Donut] across the results from the two experiments. We found some evidence that Donut [Donut] was more accurate than Bar [Bar] in all speeds. This evidence is more pronounced on Fast [Fast] and Slow [Slow]. It appears that donut charts can be read slightly more accurately than bar charts when in motion.

4.3.3 . Confidence and Difficulty

Table 4.4 exhibits how speed and representation impacted confidence rating, while Table 4.5 illustrates perceived task difficulty.

Confidence: Confidence levels differed only slightly between speed and representation. The mode for all ratings was 4 (confident), but we see a slight trend for higher answers in the Static [Static] condition for both Bar [Bar] and Donut [Donut].

Self-rated Difficulty: Participants perceived the task to be more difficult as the speed increased.

4.3.4 . Strategies

In order to understand potential differences between chart types, we asked participants to voluntarily reveal the strategies they used to read charts under motion. We received 34 descriptions from `Donut` and 40 from `Bar` participants. We excluded 1 description for donut and 6 ones for bar chart that did not describe strategies and coded the remaining into 6 groups. Composite strategies were coded into multiple groups. Next, we describe each strategy and how often it was mentioned in the two experiments. All detailed descriptions can be found in the supplementary material.

Following (13 `Donut`, 18 `Bar`): This strategy involved simply following the stimulus as it was moving on the screen.

Slicing (13 `Donut`, 5 `Bar`): Participants divided the moving chart into slices that they read. Donut participants reported using quarter slices (25%, 50%, 75%, and 100%) or two halves to make estimates, while bar participants divided the bar in halves or in thirds. The strategy was much more common for donuts.

Quick Judgment (3 `Donut`, 7 `Bar`): Some participants described estimating the value with a quick glance or saving a snapshot in their mind while ignoring motion.

Fixating (2 `Donut`, 2 `Bar`): A few participants stated that they stared at a fixed point (the center of the screen in most cases) and did not follow the movement of stimuli to make their estimation.

Other (2 `Donut`, 3 `Bar`): The strategies coded in this group were diverse and rare. Participants mentioned focusing on the smaller slice, reading the chart (better) when it moved left to right, closing one eye, and focusing on the bar end point.

Unclear (1 `Donut`, 0 `Bar`): Strategies that we could not classify due to unclear and ambiguous descriptions.

4.3.5 . Summary

In summary, speed had an impact on proportion reading performance, with accuracy decreasing with higher speeds. However, in practice, participants were still able to quite reliably read proportions from moving charts, with an accuracy that was close to 95%. Although in high speeds `Donut` was more accurate than `Bar`, in practice, their differences were small (2 percentage points). Overall, participants were confident in their answers, but the self-rated difficulty increased clearly with faster speeds.

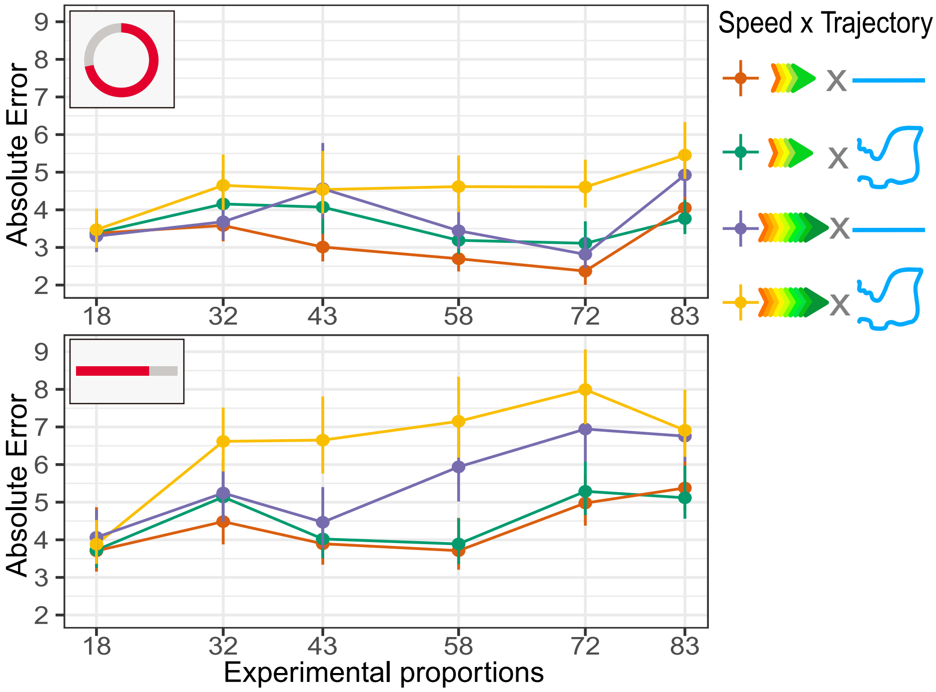


Figure 4.4: Experiment-Trajectory absolute error results for `Donut` (top) and `Bar` (bottom) per proportion.

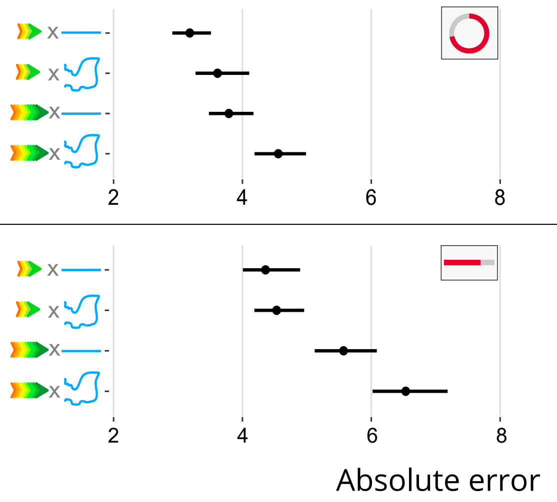
4.4 . Experiment-Trajectory (Donut/Bar) Results: The Effect of Trajectory on reading accuracy

We recruited 60 new participants per chart type in the trajectory experiments. For `Donut`, the 60 participants (31 ♀, 29 ♂; 35 students) were on average 27 years old (SD = 7.38). Participants reported just above average familiarity with donut charts (M = 6.20/10, SD = 2.59) and frequency of watching soccer matches on TV or playing video games (M = 6.60/10, SD = 3.09). The average completion time was 27.80 min, with a remuneration of £3.75 per participant. For `Bar`, the 60 participants (29 ♀, 31 ♂; 36 students) had an average age of 26.38 years (SD = 8.44). Participants also reported just above average familiarity with bar charts (M = 6.78/10, SD = 1.98), and frequency of watching soccer matches on TV or playing video games (M = 6.43/10, SD = 3.14). The average completion time was 28.57 min, with a remuneration of £4.05 per participant.

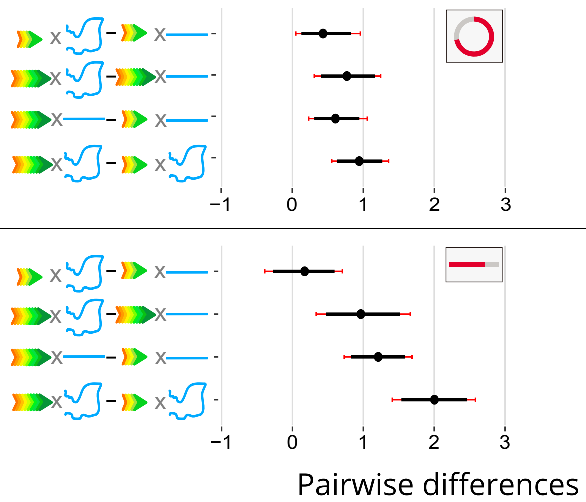
4.4.1 . Trajectory per Representation

Table 4.6 shows the participants' mean absolute error per speed × trajectory condition, the pairwise differences in absolute error across two conditions per chart type, and the differences across two representations. Fig. 4.4 shows the absolute errors split by proportion per condition and chart type.

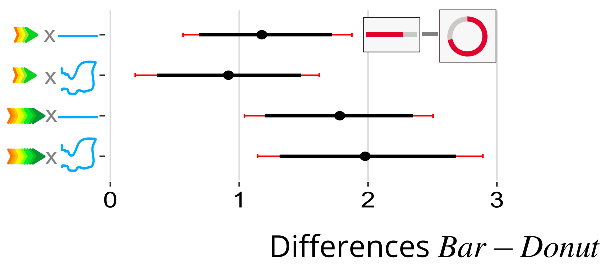
Table 4.6: *Absolute error* analysis for Experiment-Trajectory. Top: Average mean absolute error in percentage points for each chart type. Middle: Pairwise comparisons for each speed × trajectory condition and representation. Bottom: Differences of mean absolute error across representations. Error bars represent 95% Bootstrap confidence intervals (CIs) in black, adjusted for pairwise comparisons with Bonferroni correction (in red).



3.18	[2.91, 3.51]
3.61	[3.27, 4.11]
3.79	[3.48, 4.17]
4.56	[4.19, 4.99]
4.36	[4.00, 4.90]
4.53	[4.18, 4.96]
5.57	[5.12, 6.09]
6.53	[6.02, 7.18]



0.43	[0.13, 0.83]
0.77	[0.40, 1.16]
0.61	[0.31, 0.94]
0.94	[0.63, 1.27]
0.17	[-0.27, 0.59]
0.96	[0.47, 1.52]
1.21	[0.82, 1.59]
2.00	[1.54, 2.47]



1.17	[0.69, 1.72]
0.92	[0.36, 1.48]
1.78	[1.20, 2.35]
1.98	[1.31, 2.68]

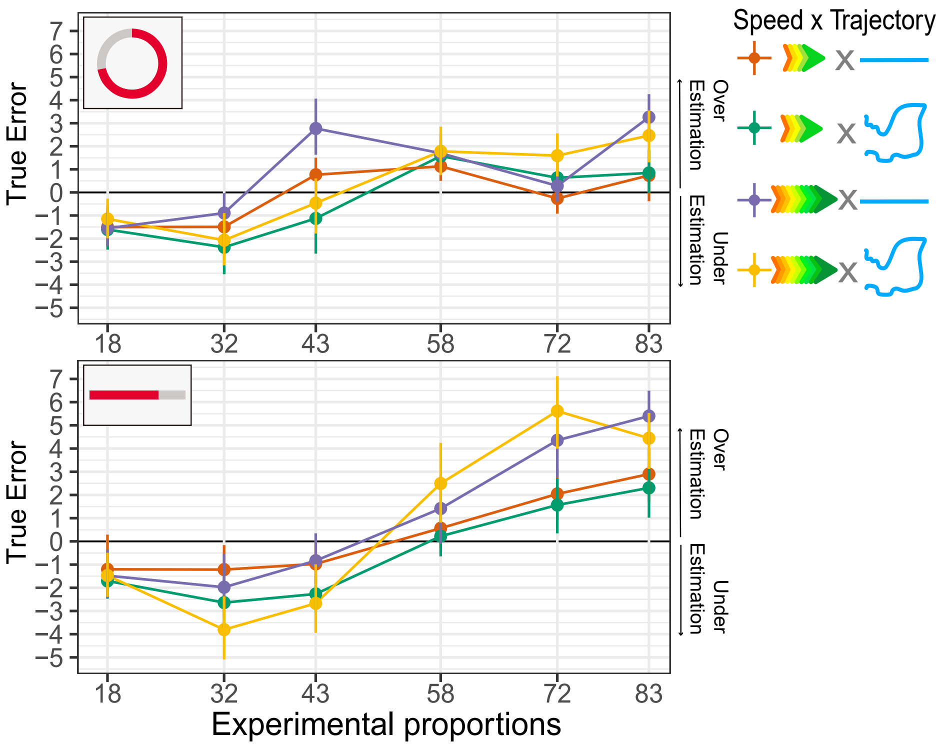


Figure 4.5: Experiment-Trajectory true error results for Donut (top) and Bar (bottom) per proportion.

Trajectories: Looking at the mean absolute errors (Table 4.6), we see that the trajectory type did have an impact on reading accuracy. Looking at pairwise differences (Table 4.6: Middle) we have evidence that `Irregular` trajectories caused more errors than `Linear` ones for both `Donut` and `Bar`, in particular at `Fast` speed. We even have weak evidence of trajectories having an impact on `Donut` moving at `Slow` speed, with `Irregular` trajectories being less accurate than `Linear` ones, while for `Bar`, we do not have such evidence.

Speeds: As expected, and consistent with the previous Experiment-Speed, for both `Donut` and `Bar`, `Fast` speed led to more errors in `Linear` trajectories and `Irregular` ones as well. While evidence of a difference between speeds does exist, we noticed that this difference is again practically very small—less than 1 percentage point for `Donut` and no more than 2 percentage points for `Bar`.

Proportions: For `Bar`, looking at absolute error per proportion (Fig. 4.4: bottom), for `Fast` speed, the degree of estimation error of `Irregular` trajectories is bigger than that of its baseline (`Linear` ones), with the exception of the smallest proportion (18%); for `Slow` speed, there is no clear difference of estimation error between the `Irregular` trajectories and the `Linear` ones

Table 4.7: Experiment-Trajectory: Confidence in the correctness of responses per condition and per representation with median (MED), average (AVG) and standard deviation (SD). 1: Not at all difficult; 10: Very difficult; SL: slow × linear, SI: slow × irregular, FL: fast × linear, FI: fast × irregular.

		1	2	3	4	5	MED	AVG	SD
SL	Donut	0	2	12	32	14	4	3.97	0.76
	Bar	0	1	13	37	9	4	3.90	0.66
SI	Donut	0	3	18	27	12	4	3.80	0.82
	Bar	0	3	19	34	4	4	3.65	0.68
FL	Donut	0	8	11	31	10	4	3.72	0.90
	Bar	0	5	22	28	5	4	3.55	0.77
FI	Donut	1	8	19	22	10	4	3.53	0.98
	Bar	1	15	22	20	2	3	3.12	0.88

across proportions. The tendencies of Donut are less clear, but we can still tell (Fig. 4.4: top) that participants' estimates of Irregular trajectories were consistently more error prone than the baseline (Linear — ones) for all proportions with the exception of 43% for Fast speed and 83% for Slow speed.

For Bar, when looking at the true error (Fig. 4.5: bottom) of specific proportions, participants again tended to underestimate for proportions less than 50% while overestimating for those greater than 50% for all speed × trajectory conditions. The tendencies of Donut are less clear, but we can still tell from the true error (Fig. 4.5: top) that for all conditions participants underestimated 18% and 32% while overestimating 58% and 83%. For 43%, participants made smaller estimation when the stimuli moving in Irregular trajectories while making larger estimation when the stimuli moving in Linear — ones. For 72%, participants underestimated under Slow × Linear — condition while overestimating under rest conditions.

4.4.2 . Trajectory across Representations

Table 4.6: Bottom illustrates differences between representations used in the two trajectory experiments.

Trajectories and speeds: When comparing the two representations directly, there is evidence that participants' answers were always more accurate with Donut than with Bar by 1–2 percentage points under the same kind of trajectory. This effect is particularly strong at Fast speed.

Proportions: For all speeds and trajectories, participants' answers were consistently more accurate on Donut than on Bar for all proportions. These differences

Table 4.8: Experiment-Trajectory: Difficulty rating per condition and per representation with median (MED), average (AVG) and standard deviation (SD). 1: Not at all difficult; 10: Very difficult; SL: slow × linear, SI: slow × irregular, FL: fast × linear, FI: fast × irregular.

		1	2	3	4	5	6	7	8	9	10	MED	AVG	SD
SL	Donut	17	18	11	4	4	2	4	0	0	0	2	2.70	1.76
	Bar	8	15	21	5	3	0	5	2	1	0	3	3.27	1.96
SI	Donut	9	11	11	9	6	5	4	3	1	1	3	3.85	2.28
	Bar	3	8	18	12	6	5	3	3	1	1	4	4.08	2.01
FL	Donut	6	4	5	12	13	5	8	5	2	0	5	4.77	2.16
	Bar	1	4	11	5	7	11	10	5	4	2	6	5.48	2.24
FI	Donut	4	4	2	7	2	8	6	14	8	5	7	6.33	2.67
	Bar	1	1	2	5	1	5	14	17	11	3	8	7.12	1.99

are particularly visible for `Irregular` trajectories and `Fast` speed, where differences reached up to 4.13 percentage points in accuracy for some of the larger proportions (58%, 72%). The only exceptions are cases (43% in `Slow` × `Irregular` and `Fast` × `Linear` condition) where the difference between the two charts is extremely small (less than 0.1 percentage point). So overall, in the majority of cases, `Donut` was more accurate by 0.33–4.13 percentage points.

4.4.3 . Confidence and Difficulty

Table 4.7 illustrates how trajectory types, speeds, and representations impacted confidence, while Table 4.8 shows perceived task difficulty.

Confidence: The mode for all ratings was again 4 (confident). We see a slight trend for higher ratings in the `Linear` trajectory and `Slow` speed as well for both `Donut` and `Bar`. Although the average confidences were consistently higher on `Donut` than on `Bar`, the confidence differences across representation were extremely small. Therefore, we cannot conclude that participants were clearly more confident in one condition than in another.

Self-rated Difficulty: Under the same speed, participants rated `Irregular` trajectories as more difficult. Under the same kind of trajectory, participants reported that they felt `Fast` speed trials were more difficult. Across the two representations, participants rated `Bar` as more difficult than `Donut`, in particular in `Fast` × `Irregular` condition.

4.4.4 . Strategies

We received 41 descriptions from `Donut` and 40 from `Bar` participants. We excluded 4 descriptions for donut and 3 ones for bar chart that did not describe strategies. We found the same groups of strategies as before and only discuss new variations here. We describe the common strategy that our participants used, followed by the remaining strategies reported.

Slicing: This strategy was again common (16 `Donut`, 15 `Bar`): In addition to the previous slicing descriptions participants mentioned to use a clock metaphor for dividing the donut and quarters for bar charts.

Following: 13 `Donut`, 13 `Bar`.

Quick Judgment: 9 `Donut`, 8 `Bar`.

Fixating: 0 `Donut`, 1 `Bar`.

Unclear: We did not collect any unclear descriptions this time.

Other: 2 `Donut`, 2 `Bar`. Other strategies used included reading the smaller slice, calculating with fingers, or blinking eyes.

4.4.5 . Summary

In summary, the regularity of the trajectory had an impact on participants' performance in reading moving proportions, the accuracy decreased with irregular trajectories and higher speeds as well. Participants again performed better on `Donut` than on `Bar`, the difference was more pronounced than in the speed experiments. Nevertheless, the differences still remain small in practice (less than 2 percentage points on average and less than 5 percentage points in all proportions). Overall, participants were confident in their answers for all tasks. The self-reported difficulty was higher for `Irregular` trajectories and for `Fast` speeds.

4.5 . Experiment Discussion and Limitations

Overall, our results showed that speed and the regularity of trajectories impacted participants' performance. Higher speed and irregular trajectories generally led to more errors. The irregular trajectories we tested were not predictable by participants which likely contributed to their poor performance. Some errors our participants made can be attributed to rounding errors caused by rounding to the nearest 5 (which was always 2 percentage points up or down from the shown magnitude). Yet, in particular for bar charts, errors were consistently above 4 percentage points as soon as motion was involved. Our experimental results do not provide evidence for a linear relationship with the increase in motion speed nor for the rise of irregularity. To establish if an exact mathematical relationship exists, future work needs to look at a larger variation of speeds and irregularities. However, theoretical limits exist beyond which viewing experiences will be severely impacted by increased blur from visually tracking objects on sample-and-hold displays; in addition to limits given by screen refresh rates. It is interesting to note though, that despite the differences we observed, the overall accuracy remained very high (95% or above) across all conditions.

We found overall better performance for the donut chart under motion compared to bar charts, but the practical difference in error between both charts was small—in the range of 1–2 percentage points. Practically, we might be able to ignore such differences and choose a representation that can be more easily embedded in the desired context of use. We had expected for bar charts to be more impacted than they were, especially for linear trajectories, as bar charts become visually compressed in the direction of motion. While differences between both charts were small, the exacerbated effect of motion blur on linear trajectories might explain why a few participants commented that the irregular trajectories were easier.

A number of participants mentioned that their task strategy did not involve following the whole movement; they briefly glanced or focused on a point and let the visualization pass by before making a quick judgment. This is interesting behavior as it might mimic how people would need to read moving visualizations as a secondary task. It is promising for future work to study how limited attention and shifting focus may affect the performance of a larger number of participants.

Studies with both stationary participants & moving targets and moving participants & stationary targets from DVA suggest that angular velocity affects visual acuity, in particular for fast velocity. While magnitude proportion judgment tasks are more complex, our results consistently show similar evidence for performance differences in our conditions involving motion. For our envisioned scenarios in sports and video games the decrease in performance we measured might be small or irrelevant in many cases. However, a difference of 4 percentage points might still make an important difference in other scenarios or certain contexts, such as when a game character is about to run out of health. In addition, it remains an open question if motion affects performance to a larger degree when viewing more complex visualizations or conducting more complex reading tasks.

One of the limitations of our study is that, due to the pandemic, we did not have the chance to run a lab study. Even though we introduced a calibration phase to make sure the stimuli were displayed at the same size and moved at the same physical speed on different screens, we still could not control the distance between participants and their screen nor the angle at which they looked at the screen. We do not know if their position in front of the screen impacted the results and to what extent it led to noise in our results. Also, our experiments were conducted on a pure white background and without important viewing angle changes. As such, our results are best-case results and performance will likely drop in a real scenario with a much more complex context involving movement in 3D space and noisy backgrounds. We imagine that in immersive scenarios such as AR/VR, the impact of motion factors would be amplified with the superposition of spatial properties.

Combined, our experiments evaluated the most basic visualizations in motion, and the results can be useful to hypothesize about impact in future scenarios. We found that:

- Higher speeds lead to more errors.
- Irregular trajectories decreased the reading accuracy.
- Participants always performed (slightly) better on donut charts than on bar charts.
- Bar charts under motion had errors consistently above 4 percentage points.
- The overall accuracy remained very high.

Regarding our research agenda (Chapter 3), our experiments necessarily explored only a small fraction of the larger research space. Our findings cannot be directly transferred to more complex scenarios such as 3D or dynamic environments. However, they can serve both as a foundation for further research and as an initial proof that reading visualizations under motion may be practical and possible.

5 - DESIGNING VISUALIZATION IN MOTION: EMBEDDING VISUALIZATION IN SWIMMING VIDEO

According to my perception studies (Chapter 4), people were able to get reliable information from visualizations moving at high speeds and under irregular trajectories. This is a promising result for visualization in motion but opens up new questions on **how to design and embed *visualizations in motion* in a real motion context**.

Many real application scenarios, including augmented sports analytics [48, 58, 167], contain simple moving visual representations related to athletes' performance and race/game metadata (Chapter 6). Nevertheless, creating, embedding, and testing designs for visualizations in motion remains difficult. Real-world contexts contain busy backgrounds and various motion characteristics. As such, visualizations in motion need to be designed to be informative but not distracting from the audience's primary motivation, such as watching the race.

I selected swimming as my target motion context as swimming has rich and dynamic data that is already visualized but to a limited extent. I first conducted **a systematic review** to investigate the visual representations used, the data encoded, and the movement status of the visualizations embedded in swimming races. I next ran **an online survey** to clarify the real data needs of swimming race audiences. Following, I conducted **an ideation workshop** to collect diverse visual representations designed for the swimming context. I then developed *SwimFlow* [35] as **a technology probe** [2] to investigate the significance of the full motion context in the design process and the impact of instantaneous visual feedback of motion effects on the design decisions of *visualization in motion* (screenshots of examples made by *SwimFlow* can be seen from Fig. 5.1). I ended this work by conducting **a design evaluation** and proposing **a set of design considerations** for *visualization in motion*.

> This chapter is an updated version of the text from my original article published at *IEEE Transactions on Visualization and Computer Graphics [168]*. The article was led by myself and co-authored with my supervisors and collaborator: Romain Vuillemot, Anastasia Bezerianos, and Petra Isenberg. In the following content, I switch from "I" to "we" to describe our work.

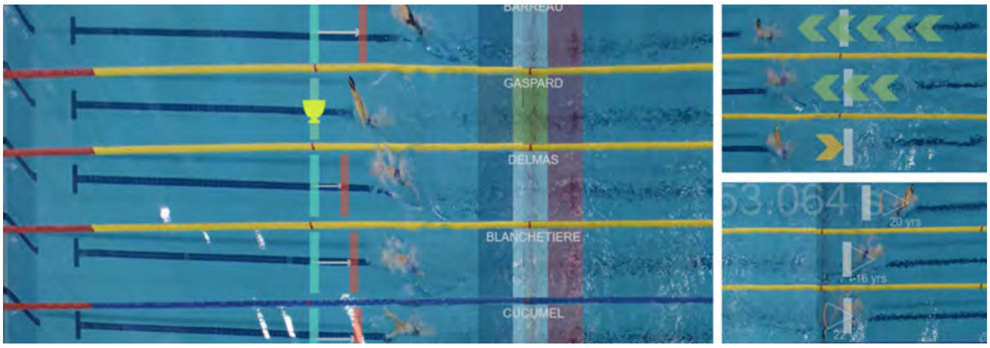


Figure 5.1: Embedded representations added to a swimming video of the 2021 French Championship using our technology probe. These show dynamically updating visualizations that move with the swimmers: distance to the leader and predicted winner (left), speed distance to a personal record (top right), and current speed and swimmers' ages (bottom right). The left and bottom right images also show stationary embedded representations of the swimmers' names, nationality, and elapsed time.

5.1 . Related work

Our own past work introduced the concept and a research agenda (Chapter 3) for visualization in motion and first evaluations (Chapter 4) that analyzed important motion features that may affect the readability of visualizations in motion and factors to consider in their design. Nevertheless, this prior work did not consider the design process and challenges in the design of such visualizations and did not investigate a concrete design scenario. Here, we work concretely in the area of sports visual analytics and swimming in particular as a use-case. Consequently, we review how visualizations have been explored, designed, and embedded in videos. We complete the related work by discussing relevant related authoring methods for such embeddings.

5.1.1 . Sports Visual Analytics

Situated visualization has gained a lot of traction in the augmented reality community. In their SportsXR work [97], Lin *et al*. provided several case studies of situated, sports-specific visualization designs in immersive environments for training, coaching, and fan experiences. Like us, the authors argue that videos play a central role as a situating context for visualization but that the data remains a challenge to extract accurately. Videos also play an important role not only as a reference [169] but also as a validation mechanism in that displayed data can be compared with the original scene. VisCommentator is related to our work in that it explored the combination of visualizations and computer vision with sports videos. The tool can, based on user selection, embed both static and animated visualizations in videos [51]. In contrast to our work, the visualizations are animated but not in motion according to our definition. Early work on soccer videos [56] maps players' controlled zones on the soccer pitch, but only in single video frames.

Several companies (like Footovision [48] or SportsDynamics [49]) now commercialize video augmentation tools that allow to embed simple statistical graphics in sports videos, often for highly funded sports such as soccer or basketball. In contrast to our work, the underlying technology is not grounded in empirical work and often focuses on simple effects and highlighting. Visualizations in these tools seem to be inspired by situated visualizations in other video-related domains, such as video games [170]. Here, tiny visualizations, like health bars, are often attached to game characters and move with them. The research work most closely related to ours is embedded basketball visualizations for in-game analysis [57, 58]. In contrast to our work, Lin *et al*. [58] focused on studying how viewers would control the visibility of the visualizations, and iBall [57] helped casual fans understand the game. Instead, we focus on how to support the design process of the visualizations and their embeddings.

Our work is also related to efforts in the visualization community that provide a novel lens on various sports data. Perin *et al*. [171] summarized designs that demonstrated the potential of sports visualization for both narrative and analytical processes. Most sports have been visualized even if only little data was available. Examples include tools for table tennis [51, 52, 172, 173], soccer [56, 174, 175], basketball [59, 60], badminton [62, 63], and tennis [176]. With a specific focus on swimming, Kiss *et al*. [177] designed a wearable device called Clairbuoyance to help swimmers to better perceive their moving direction. Unlike us, this past work mainly targeted professional coaches and athletes.

We complement this past work we discussed by studying how to support the design process of creating embedded visualizations in motion based on real data needs and videos.

5.1.2 . Authoring Tools for Adding Visualizations to Videos

Authoring tools for visualization allow users to create bespoke visualizations in a graphical user interface without programming. In their critical reflection on authoring tools [178] Satyanarayan *et al*. review three tools: Lyra [179], Data Illustrator [180], and Charticulator [33]. These and other tools focusing on powerful and creative data to mark mappings and configurations [34], [181], are built around the creation of static, non-moving visualizations. While we also provide authoring components in our technology probe, we focus on the discovery and implementation of features needed to design for the situated and moving context in swimming videos. Our probe is thus not as flexible and powerful as the fully-fledged past approaches for authoring bespoke visualizations.

Besides work on GUI-based authoring, researchers have also explored other novel methods. Sporthesia [50] is an example authoring system that takes a language-driven approach in the sports context where visualizations are automatically created based on commentary on the sports activity. Work in Augmented Reality (AR) has looked at how to design visualizations for a dynamic context. For example, RealitySketch [182] can attach simple statistical charts on a video based on tracked objects. The sketched charts relate to spatial data extracted from the object tracking. MARVisT [183] is an authoring tool for the general public. It embeds glyph-based visual representations in AR by binding the glyphs to objects in the environment.

More broadly, our work relates to work on data videos. Data videos attempt to tell a story using videos and data visualizations as a medium. Much of the literature centers around questions of how to create visualizations in videos to form a coherent narrative and an enjoyable watching experience [184]. Some work, however, has also considered how to embed charts directly in videos [169, 185]. In their design guidelines, Tang *et al*. [169, 185] mention motion factors, but these are primarily related to animating visualizations. Yet, several of their designs and data-related considerations are relevant to us even though the authors considered non-sports-related videos. The authors recommend using colors that are in harmony with the videos, appropriate visual mappings, placing visualizations next to objects in the video, and avoiding overlap. Their design goals similarly apply to our context, *i.e.*, to avoid conflicts between visualization and video intent, enhance perception, increase appeal, reduce cognitive load, emphasize the data, and keep consistency.

Ultimately, our goal is to improve our understanding of design processes that best allow designers to juggle these important factors in the creation of embedded visualization in motion.

5.2 . Data Exploration & Visualization Ideation

In order to base our exploration of design processes for situated visualizations in motion in current practices and real data needs, we followed a three-step process. We first analyzed current data and visualizations embedded in example swimming races. Our findings were then inspired to inform the creation of a crowdsourced survey that we ran to explore what an extended set of data audiences might be interested in seeing during swimming competitions. Our survey was pre-registered at `https://osf.io/qdbhg`. Finally, we conducted an ideation workshop to generate designs corresponding to the data items that were most interesting according to our survey. Our goal was to elicit designs but also to see how participants would fare with a traditional design method in this context.

5.2.1 . Review of Current Practice

To understand how to support the design process of embedded visualizations best, we first studied the limited examples of embedded visualizations in swimming. We explored how visualizations are currently embedded in swimming broadcasts from three aspects: (a) which data is displayed using which representation, (b) visualization movement and placement on the screen, and (c) under which camera

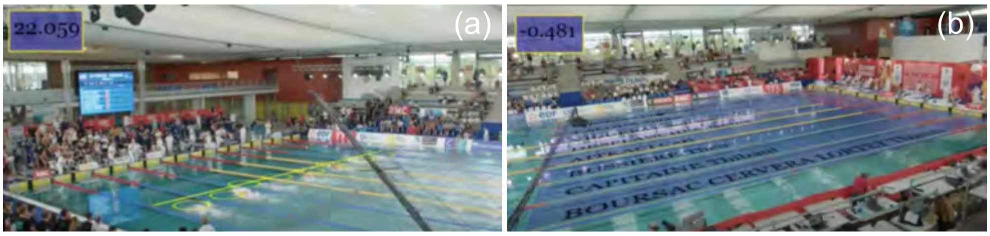


Figure 5.2: Recreated examples of embedded visualizations for swimming from an internal prototype. (a) Swimmers' current position circles and record line moving with the swimmers' movement. (b) Stationary swimmers' names in each lane. (a)(b) have a stationary timer in the top left corner. (Due to the issue of image permissions, these examples are from our own corpus).

positions and perspectives. To explore these embedded visualization practices, we looked at a large corpus of videos, including the Olympics from 2008—2020, as well as the latest FINA world championships and the French national in their latest instance. We chose to focus on the 2020 Olympics races because they used more embedded representations than any of the other races.

The videos we analyzed covered all 4 strokes (freestyle, backstroke, breaststroke, and butterfly) and all 5 race lengths (50m, 100m, 200m, 400m, and the 4 $\times$ 100m medley). We looked at the race from the start signal until the last swimmer finished their race.

Visualized Data and Representations: We classified the data visualized in the current races into swimmers' metadata, including nationalities, names, and lane numbers; temporal information, such as the time taken from the start of the race to the current time (elapsed time) and the lap time difference between swimmers and a specific record; record-related information, like the word and the competition record; speed-related data — current speeds; and distance-related data — distance swam. Apart from the nationality represented by a flag and the record shown by a colored line (Fig. 5.2 (a)), all other data was displayed in text (*e.g.*, in numbers (Fig. 5.2 (b))).

Reflection: These data can be grouped into `dynamic` data, whose value changes over the course of a race (*e.g.* speed), and `static` data, whose value stays consistent (*e.g.* nationality). We noticed that the current visualized data covers only a very small part of the data that can be collected about swimming races. For example, the distance between two swimmers can be easily calculated according to the distance swam, and it is possible to predict if a swimmer may break a record. To more broadly cover potential data to be visualized, we first created a data matrix with the categories identified in the videos and were reported before (5 data categories and 10 data items). We then expanded the classification of the data matrix through discussions with swimming practitioners and swimming-focused researchers who understand other data that can be captured

Table 5.1: Swimming data matrix with example data items. A yellow highlight indicates the data items that are visualized statically in current swimming races; purple highlights the data captured and shown in motion. Elapsed time is the time gone by since the beginning of the race. Lap time is the time taken to complete one length of the pool. History of speed is a continuous time series representing the speed changes in the race. A passing happens when a swimmer overtakes another swimmer. A stroke is an arm movement with a specific technique used to propel the swimmer through the water.

Dynamic Updating Data					
Time related	Elapsed time	Current lap	Average lap	Lap differences to other swimmers	Lap differences to a record
Speed related	Current speed	Average speed, Speed history	Acceleration, slow down	Speed differences to other swimmers	Speed differences to a record
Distance related	Distance swam	Remaining distance	Distance differences to leader	Side-by-side distance between two swimmers	Trace of movement
Predictions	Record break	Winner	Completion time	Next passing	
Swimming techniques	Distance per stroke	Reaction time	Diving distance	Stroke count	
Static Data					
Swimmers' metadata	Nationality	Name	Lane number	Age, Gender	Height, weight
Record related	World record	Competition record	National record	Personal record	
External	Social Media followers	Social Media discussion	Sponsor		

during races and that they expressed particular interest in (an additional 3 data categories and 27 data items). The final data matrix can be seen in Table 5.1. Our data matrix includes 8 categories (with 37 example data items): `time-related`, `speed-related`, `distance-related`, `record-related`, `external` data, `predictions`, `swimming techniques`, and `swimmer's metadata`.

While we identified a large number of data items that could be visualized, which data might interest the general audience remained unknown, and how best to visualize them in the context of swimming races was similarly unclear. To address these questions, we followed up with an online survey (Section 5.2.2).

Movement Status and situatedness: The majority of the currently visualized data in swimming videos stay stationary and do not change position on the display. Exceptions we found were speed labels and record lines, *i.e.*, when swimmers were close to the end of their lane, a speed label, composed of the text of their current speed and a flag for their nationality, followed the movement of the swimmers.

Record lines (Fig. 5.2 (a)) moved at the record holder's average speed[1]. These two moving visualizations were embedded close to the swimmer or embedded in the swimming pool (Fig. 5.2 (b)). The remaining visualized data remained static on the screen, usually in corner positions, with a large distance to the swimmer they were referring to. (*e.g.*, Fig. 5.2: timer).

Reflection: We saw that compared to the early Olympics videos (2008) we had initially looked at, the 2020 videos we analyzed included a more diverse set of embedded visualizations. We also saw that existing visualizations became more detailed, for example, by adding labels to explain the visualizations themselves. This might indicate an increased interest of audiences and public broadcasters to see and show embedded visualizations in sports. Yet, how to design future visualizations, how to attach them to a moving reference (*e.g.*, a swimmer), and how to define their movement paths remain an exploration. In addition, there are currently no tools to let designers easily experiment with different designs, for example, trying different visualization placements around a moving target and testing that the visualization remains legible throughout the moving trajectory or checking if the data's update frequency is too slow or too fast and thus distracting. In order to explore features of future prototyping tools for embedded visualizations in motion, we developed a technology probe [2] we call *SwimFlow* (Section 5.3).

Camera Positions and Perspectives: Camera positions and viewing placements are important for embedded visualization design, as they may influence how visualizations may move wrt the screen (camera position) and how often they may need to be positioned (changing perspectives). We found multiple camera perspectives used in swimming videos. These perspectives were shown from cameras positioned around the pool or cameras placed underwater. The underwater perspectives were usually only shown briefly to highlight a small number of swimmers, often even only focusing on a single swimmer. Future visualizations shown in underwater scenes could benefit from the pure and consistent blue background of the pool, with very little visual interference (such as a few lane lines). The perspectives from outside the pool were more common. They allowed us to see overviews of multiple, if not all, swimmers and, as such, might be better for including comparative visualizations. On the other hand, these perspectives come at the cost of a more noisy and colorful background context to place the visualizations in (multiple lane lines, audiences, reflections, lighting, *etc.*). These camera perspectives outside and around the pool included a bird's-eye view (top), side views, diagonal views, and transitions between them. In the diagonal view, swimmers swam along the diagonal of the screen – from the bottom right to the top left or from the bottom left to the top right corner.

Reflection: Similar to many other sports, swimming broadcasts change perspec-

[1] In swimming, a record is recorded as the time taken to complete a certain distance.

Table 5.2: Participants' swimming race familiarity:
distribution of races watched and their watching frequency.

	Olympics	International	Continental	National	Regional
All races	15	8	5	3	1
Almost all races	29	15	13	12	4
Some races	32	33	33	29	15
No races	4	24	29	36	60

tives frequently and also include moving cameras that pan and rotate. For example, it was common that when swimmers turned around, the camera switched from an in-air to an underwater perspective and moved close to focus on the current leader. Consequently, not only did the swimmers' positions change on the screen, but also the swimmers' sizes and the angles from which they were shown could change within a few seconds or even less. For embedding data in swimming broadcasts, this means that viewers will have to be able to track visualizations across perspectives and be able to deal with the complexities of changing backgrounds and motion added by the camera movement.

5.2.2 . Surveying Data Interests

As we saw previously, despite the large types of data tracking that may be of interest to audiences, currently visualized data in swimming races are quite limited, and embedded visualizations in motion are even rarer (Table 5.1). There might be many reasons behind this scarcity of embedded visualizations: designers might not be aware of what audiences want to know, they might be afraid of causing too much distraction, or they might not have the data available. The first two challenges can be addressed by visualization research, the latter being more of a problem for computer vision and dedicated prototyping tools. Here, we start by providing a first empirical investigation of the data needs of swimming audiences and then move on to discuss how to support the design process. Our survey was pre-registered at `https://osf.io/qdbhg`.

Survey Procedure: We proceeded to conduct an online survey on LimeSurvey [186] to gauge general audiences' interest in specific data while watching swimming competitions on TV or live stream. We advertised the survey to swimming associations, on social media, and at our poster presentation on our national visualization day [187]. We collected basic demographic information and the frequency at which participants watched certain important swimming races on TV. Since the visual encodings embedded in the broadcast might differ by region, participants were also asked to report their broad geographic location. The main part of the survey asked participants to rate their interest level per data item (Table 5.1) on a 5-point Likert scale from not interested at all to extremely interested, with an extra option "I do not know/I did not understand the question." In order to avoid people choosing the last option, we gave participants access to explanations for each data item. We also allowed participants to add any data items of interest that they could not find in our list. The order of data categories, as well as data items, was randomized per participant. During the description of results, we make use of the data type icons from Table 5.1 and the representation icons in Section 5.2.1. For example, a static representation of metadata using a symbol would be described as : × [].

Participants: In total, we gathered complete answers from 80 volunteer participants: 27/80 ♀, 52/80 ♂, 1/80 unspecified; 65/80 lived in Europe, 8/80 lived in North America, 6/80 lived in Asia, 1/80 lived in Africa; the ages of participants ranged from 18 to older than 75 [2]. Participants' familiarity with swimming races is reported in Table 5.2. 75/80 participants reported that they had already seen visualizations in motion on TV in the form of nationality flags (: × []), current speed text (: × []), and record lines (: × []).

Results and Findings: Participants' interest in each data item is depicted in Fig. 5.3. In blue on the right is the percentage of participants who expressed interest. Labels for data items with an interest level over 75% (30/37) are shown on the left, while the remaining labels (7/37) are on the right. The data items added by participants are not shown in the figure because they were rare but can be found in Appendix - Section II.

Data Categories of Interest: Out of the data items that received an interest level above 75%, 20/30 belonged to `dynamic` updating data, while the remaining 10/30 were `static` data. Participants found all `time-related`, `speed-related`, `predictions`, [:::] `swimming techniques`, and `record-related` interesting, while `external` data received the least amount of interest.

Data Items of Interest: The three data items we found moving with swimmers in the past Olympic broadcasts (current speed, flags, and record lines) received high-interest rankings (above 89%). The world `record` in particular was ranked as extremely interesting by participants. However, we also saw data items at the top of our list that were not yet part of current broadcasts. The `distance` between the current leader and other swimmers stood out with the second highest rating.

Our participants also expressed interest in other subtle differences between swimmers, including `time-related` and `speed-related` data, such as the lap time differences and speed differences to a record and/or other swimmers. Of these, we have only seen lap differences from the world record be briefly displayed at the turning point in races at the national level or higher.

In addition to the differences between swimmers, our participants showed a keen interest in the swimmers themselves. This makes sense since the requirement to wear swimming caps and goggles and being submerged in water makes it difficult to identify who is who. Therefore, it is not unexpected that participants highly valued

[2] distribution of age range: 18-24, 25-34, 35-44, 45-54, 55-64, 65-74, >=75

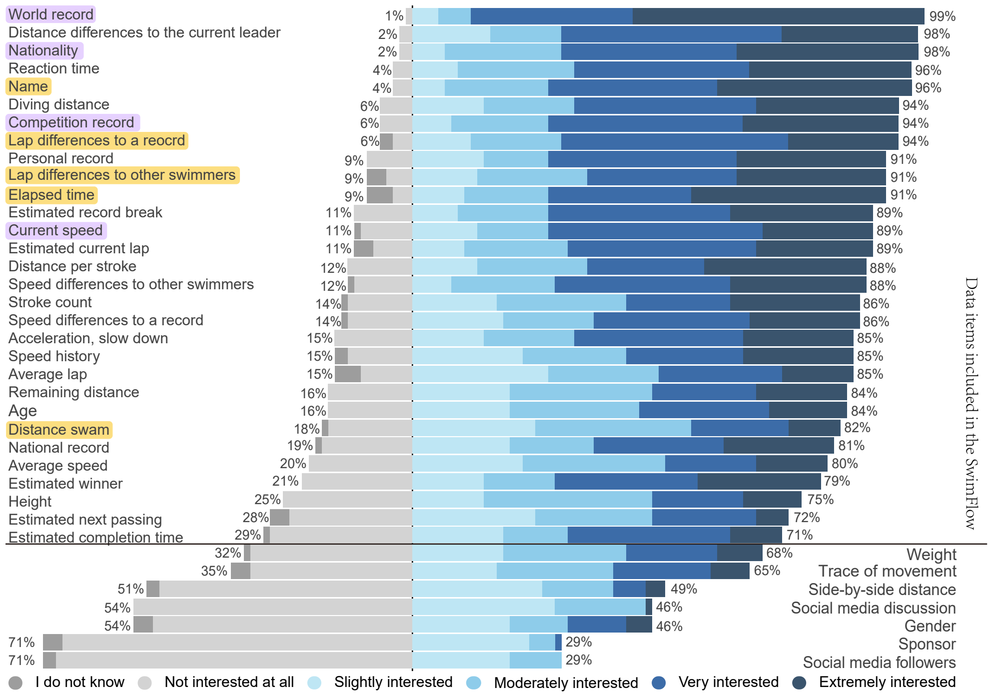


Figure 5.3: Survey results: Participants' interest level in seeing visualization in swimming races for each data item. A black horizontal line separates the data items included in our technology probe (Section 5.3). A yellow highlight indicates the data items that are already visualized statically in current races; purple highlights the data visualized in motion.

`swimmer's metadata`, such as their names and personal records. Surprisingly, our respondents were also highly interested in `swimming techniques`, including the swimmers' reaction time and the diving distance. This data is not only absent from current Olympic broadcasts but also rarely orally mentioned by commentators.

Of the data that was the least interesting was some we had considered interesting ourselves: swimmers' movement trace, for example, and the distance to neighboring lanes did not attract much attention from our respondents. Gender was also not of much interest, perhaps because the mixed-gender medley only made its debut at the 2020 Tokyo Olympics.

In summary, our survey showed a huge potential for augmenting swimming videos with embedded data about the race. Only 11 of our 37 data items had interest levels below 80% and we found many data items of interest that are not yet common in public swimming broadcasts.

5.2.3 . An Ideation Workshop

The main goal of this ideation workshop was to elicit possible representations for popular data items for our technology probe. In addition, we observed challenges

Figure 5.4: Workshop procedure: A participant (a) sketches her design on a transparent sheet with a printed background below, and (b) presents her design by attaching the transparent sheet on a whiteboard for all others to see.

of traditional sketching as an ideation technique [188] for motion context. The participants of our workshop were 4 senior visualization researchers (including two co-authors) and 3 students (2 Masters and 1 PhD student) working in the area of visualization. The workshop was led by the first author of this paper, who did not participate in the exercise.

Procedure: The facilitator first presented a summary of the review (Section 5.2.1), as well as the results of the online survey (Section 5.2.2), and introduced the available sketching materials (*e.g.*, pens, transparent sheets, and background images). Next, she asked participants to complete one design round per data category (Table 5.1). In each round, participants had 10 minutes to sketch a design (Fig. 5.4 (a)) and 3 minutes to present (Fig. 5.4 (b)). Participants sketched their designs (Table 5.1) on transparent sheets placed over one of five printed random frames from the women's 200m butterfly final at the Tokyo 2020 Olympics [189]. Participants could slide their transparent sheets over the background images to simulate a moving effect. At the end of the workshop, participants voted for their favorite designs.

Designs and Results: We saw a variety of designs (n=46). People drew representations already seen in broadcasts (nationality flags, lines, and text) but also a variety of new representations. This is not surprising as all participants had a visualization background. We grouped the sketched visual representations into 4 categories: `graphics` (21/46) are small pictogrammatic, iconic, or symbolic graphics that may indicate positions and categorical information. They may also be custom data-driven graphics akin to data glyphs that change shape based on data. Examples include flags to show who is predicted to win or arrows whose length and width encode the distance to a leader; `lines` (14/46) are representations of absolute or relative positions drawn to represent, for example, record lines, position traces, or two parallel lines whose position indicates a distance difference; `text`

(15/46) is used to write out quantitative or categorical information, for example, the current race time or the name of a swimmer, and `charts` (11/46) are traditional data representations such as pie, donut, or bar charts. 32/46 visualizations were designed to connect directly to the `swimmers` and move with them, while 14/46 visualizations were located relative to the `swimming pool`. Participants tended to embed simple data items, such as the current speed, as close as possible to the swimmer, sometimes even overlapping with the swimmer. Participants preferred to attach more complex data items, which require more display space, to the swimming pool even if the data was dynamically updated. For example, some participants attached a visualization about when and where a subsequent passing will happen to the side of the pool. 16/46 visualizations combined multiple representations, such as dynamically updating data with annotations and comparisons between/across swimmers.

Sketching Challenges: We had prepared the sketching exercise in a way that would allow people to experiment with motion using transparent overlays akin to sketching techniques for user interactions [190]. In practice, we observed that this did not work very well for the participants. Motion factors could only be tested well when the underlying images of the pool included no perspective distortion; when a design was overlayed on a pool screenshot taken at an angle, the design would slide into different lanes when the transparent sheet was moved, and the fact that the design did not correctly change size became disturbing. Moreover, moving components that could affect visuals, such as the visible part of the swimmer, splash, and shadows, could not be accounted for. Besides, the movement effects of sliding the transparent sheets are only a part of the factors that need to be taken into account — the asynchronous motion between background, data referent, and visualizations made it additionally difficult for participants to imagine what their designs might look like, especially when the designs showed dynamically updating data.

5.3 . Towards In-Context Editable Vis in Motion: A Technology Probe — *SwimFlow*

To be able to study how to better design for the motion context, we implemented a technology probe — *SwimFlow* that includes a set of basic features for prototyping visualizations in motion coupled with a video. Technology probes [2] are simple, flexible technologies used to field test the usage of technology in real-world settings. They are not prototypes of fully functional systems but instead are tools to inspire ideas for new future technologies. As such, our probe includes the basic requirements for deployment with designers: real data, an underlying video, a simple set of visualization authoring features, features to define the embedding of visualizations in the video, and video playback options. In this section, we first describe the design of *SwimFlow*, followed by the process of preparing video and tracking data, and end the section by introducing its components. *SwimFlow* can be found at https://github.com/lyao0219/SwimFlow. A demonstration video of *SwimFlow* can be found at https://youtu.be/yC39NXBJiE8.

5.3.1 . Authoring Probe Design

SwimFlow (Fig. 5.7) targets designers, or users with a background in graphics design and who regularly use prototyping tools as part of their workflow. *SwimFlow* allows users to synchronously embed visualizations, edit designs, and preview motion effects corresponding to the moving entities in a playable video. While we identified the need to support multiple camera positions and perspectives in our exploration of current practices, for our probe, we decided to use only a single perspective. Including multiple perspectives would have required us to have a much more complicated tool and data backend than we needed to study the prototyping of situated visualizations on video. As such, we chose to provide a bird's-eyes view that gave a good overview of the entire pool and all swimmers and a stable visual focus. Thus, any issues found in designing with our probe and camera view would also affect more complex design settings. *SwimFlow* has three main parts: (a) a demo video with attached tracking data, (b) a set of visualization layers over a playable video, and (c) an interactive interface. The visualizations are rendered as overlays over the video — using tracking data, visualizations can move synchronously with data referents but stay on their own visualization layer. The separation of the video and visualization layer allows us (a) to achieve smooth motion and (b) to make it possible for *SwimFlow* to adapt to various videos and shot types. We developed the interface using web technologies, including JS, HTML, and CSS. The graphical implementation and motion rendering were realized on a Canvas object. We prepared the video we currently use in *SwimFlow* as well as its tracking data ourselves to avoid later copyright issues with sharing our work.

5.3.2 . Video and Tracking Data Preparation

To have a fixed spatial reference system, the demo video embedded in *SwimFlow* underwent several pre-processing steps, including combining two videos, which were recorded separately from the side stands of a swimming pool (side view: Fig. 5.6 (a)(b)), into a unique video *as seen from above* (bird's-eye view: Fig. 5.6 (c)). Here, we describe our video combination, which we realized using a standard computer vision warping technique and our tracking data extraction. All scripts and tools are in the supplementary material.

Video Recording: We recorded multiple swimming races during the *2021 Montpellier French National Championship*, with the authorization of the French National Swimming Federation (FFN [36]). We used the Women 100m breaststroke video in our work. We set up two side-by-side cameras (Fig. 5.5), as one camera could not cover the entire pool or would have created too much distortion due to a Fisheye effect. Each camera covered half of the swimming pool and captured the race in 4K resolution at 50 frames per second.

Figure 5.5: Video recording setup: left and right cameras independently recorded half of the pool.

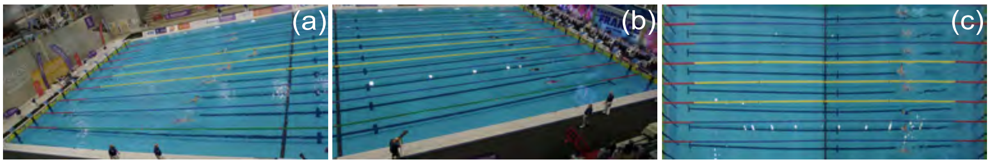


Figure 5.6: Screen shots of the self-recorded video from the left (a), the right (b) camera, and the final combined video of a simulated bird's-eye view (c).

- To remove unwanted camera movements, we detected key points on every frame to achieve *video stabilization* (usually the field landmarks, such as the center and the corners on most sports fields or the distance markers alongside the run tracks).
- For two videos to be played simultaneously, we manually selected 4 representative points of each half side of the swimming pool to achieve *homographic projection*. Then, we calculated the video transformations to simulate a camera as seen from above the pool using the OpenCV 4 `warpPerspective` function.
- To reach color balancing and purify the background, we matched color tones and calculated the median image to achieve *background homogenization*.

Tracking Data Annotation: Regarding the tracking data that captured swimmers' positions, we manually annotated the video using an in-house annotation tool (similar to labelImg [191]) designed explicitly for annotating swimmers' positions. As annotating swimmers' positions for each video frame is time-consuming, we annotated the *(x, y)* coordinates per swimmer per stroke (*i.e.*, for breaststroke, occurring, in general, less than one second. We annotated positions when the swimmer's head was at its highest). To obtain continuous tracking data for each video frame, we interpolated strokes by multiplying the average speed between two strokes and the delta time per video frame.

5.3.3 . User Interface Introduction

SwimFlow contains many features. Instead of describing them individually, we group features by function type. Each group of features contains multiple UI elements. Since our goal was to ultimately use *SwimFlow* as a technology probe, we did not attempt to implement features as complex as those present in other visualization authoring systems (see Section 5.1.2).

Setup (S): Designers begin by selecting a data item to represent from a drop-down menu (Fig. 5.7 (S.1)). The dropdown menu contains all data items with an interest level over 75% from our online survey—together with a donut chart of its exact interest percentage. Next, users can choose from a pre-defined representation we made available based on the designs collected in our workshop (Fig. 5.7 (S.2)). Other pre-defined visualizations can be easily added to the probe. Once data and a basic representation are selected, the designer can proceed to customize the visualization and its embedding parameters (Fig. 5.7 (R)) and play it back (Fig. 5.7 (P)).

Visualization and Embedding Customization (R): A set of core features of *SwimFlow* concerns the specification of the embedding of visualizations. Designers can select for which lanes the visualizations should be displayed with a *lane selector*. Designers can also specify for which data referents (swimmers or lanes) to display the visualizations. By default, visualizations are set to be connected with `swimmers` and move with them. Users can move the visualizations above/below the swimmers or closer/further to the swimmers by dragging position sliders. Users can switch the data referent from `swimmers` to the `swimming pool` by turning off the *"move with swimmer"* switch. Once turned off, visualizations will remain at the position where they last stopped. The position controls will now act in reference to the swimming pool (Fig. 5.8). The added *align* switch can be turned on to align visualizations and edge buttons can be clicked to embed visualizations at one of the 4 edges of the pool.

SwimFlow also provides the flexibility to flip the moving visualizations' position when swimmers turn. With a pressed *flip button*, a visualization behind the swimmer during their forward movement will automatically flip to be in front of the swimmer after their turn (Fig. 5.9). Additionally, representations with an orientation property, such as an indicated arrow, will be automatically mirrored once the swimmer turns.

Representations can be modified in terms of their size, rotation, color, and

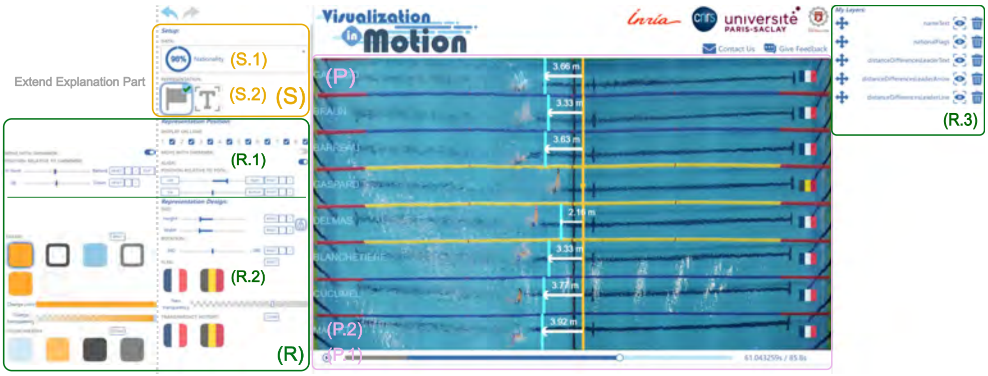


Figure 5.7: *SwimFlow*: (S) Setup: Data item (S.1) and representation (S.2) selectors. (R) Embedding parameters - R.1: a lane selector, a switch to attach visualizations to swimmers or the pool, a switch to align visualizations, and sliders to modify the distance between visualizations and their data referents; Visual encoding parameters - R.2: Sliders to adjust size and rotation, a color picker optionally accompanied by a transparency slider, and layers; Visualization combination - R.3: a layer panel to adjust the visibility and hierarchy of visualizations. (P) Playback: a video play/pause button with a video progress bar (P.1), accompanied by a video (P.2).

transparency. Users can manipulate sliders to modify the height and width of `graphics`, `lines`, and `charts`, as well as the font size and stroke weight of `text`. A color picker and transparency slider allow to modify colors for most elements (except for certain graphics such as flags). When a color is modified, a color history block is created to aid in the reuse of colors.

A *layer* panel similar to those in common graphic editing tools (Fig. 5.7 (R.3)) allows to combine multiple visualizations. Users can save the current design to layers and adjust the overlapping order by dragging and dropping the layer labels. Users can directly reload an already saved layer by single-clicking the layer name or rename layers by double-clicking. Users can make a visualization invisible for all lanes by clicking the visible icon or delete a visualization for all lanes by clicking the trash icon.

Playback (P): To test how a visualization appears under motion *SwimFlow* incorporates a video play/pause button and a video progress bar (Fig. 5.7 (P.1)), giving users the ability to not only see the visualizations move but also to get a

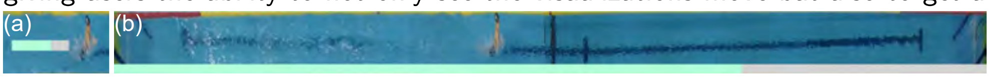


Figure 5.8: Remaining distance indicators once attached to and moving with `swimmers` (a) and attached to the bottom edge of each lane of the `Swimming pool` (b).

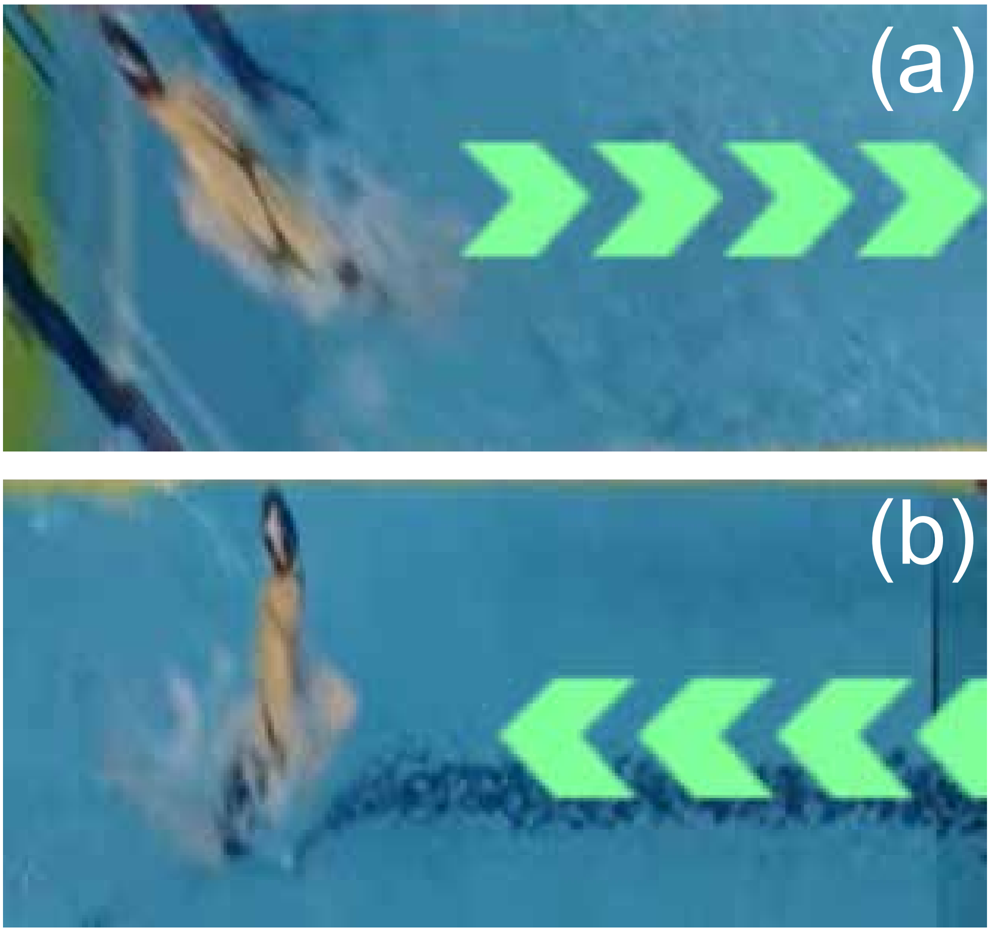


Figure 5.9: The position of the acceleration graphic (a) is flipped after their turn (b), and its direction is mirrored.

feel for how the represented data changes over time. The designs can be modified while the video is either playing or paused.

Additional features: *SwimFlow* also includes undo/redo buttons in the top left corner that act on the currently selected data item and actions performed on its current representation. Furthermore, users can share their designs as non-modifiable playable videos via a shareable link offered by *SwimFlow* [192].

5.4 . Effects of Motion Context: A Design Study

To understand the impact of real motion as a context during the visualization design process, we ran a design study with *SwimFlow*. Specifically, we wanted to identify the specific benefits of designing directly inside the video context. As one can perhaps already gauge from the previous sections, future tools for designing embedded visualization in motion will have to be feature-rich and will take considerable effort to develop. Whether the benefits of prototyping in the context of videos will be worth the required development effort is one main question we asked ourselves. As such, we wanted to compare the design of embedded visualization on still images to the design of visualizations on a playable video. Our participants were 8 graphic designers who had visualization experience and could, thus, reflect on the impact of motion on their process. Our study was pre-registred at `https://osf.io/fw7gj`.

5.4.1 . Method & Procedure

The purpose of this design study was to explore the design process for visualizations in motion in the absence and presence of an underlying playable sports video. We had initially planned an online experiment but changed to an in-person one for all but one participant. For the first participant, we conducted a video call but found that the resources needed to run the online session interfered with a smooth design preview experience; we then switched to in-person experiments for all subsequent participants.

The study was divided into two phases. In the first, designers created their visualizations using *SwimFlow* on a static screenshot from the video. After they had completed their design, we showed them what their design looked like on the video. In the second phase, participants could further refine their design on the video with all features for video playback enabled. The study lasted approximately 1 hour. We collected quantitative and qualitative feedback to understand the differences between the two design processes.

The study began with a consent form and a short demographic questionnaire. Next, we showed participants an Olympics swimming video to give them an understanding of the context and application scenario they would be designing for. This video was followed by a tool tutorial video and a 5-minute tool exploration time in which participants could experiment with the visualization generation and embedding features. Then, participants began Phase 1:

`Motion-limited mode`: We presented a stripped-down version of the tool that practically only showed a screenshot from the video. There was no play/pause button and no video progress bar. Designers could use all features of *SwimFlow* related to setup (S) and data visualization (R) but could only preview their design on the static video frame. By changing the position of the visualizations, participants could simulate movement. However, similar to the sketching scenario in our workshop (Section 5.2.3), there was no dynamic update of the visualized data nor any movement of the swimmers. This was done on purpose, acting as a baseline to study the challenges of designing without dedicated motion support. We asked participants to create at least 3 data representations but gave no upper limit. Participants had 15 minutes to complete this phase. Once the time was up, they were allowed to finish the design of the visualization that they were currently working with but not to add new ones. We then asked our participants to rate on a 7-point Likert scale how satisfied they were with their present design. Next, participants visited a link to see a playable video with all their designs embedded. After participants had previewed their designs on the playing video, we asked them to rate their satisfaction again with the same rating scale. We then conducted a first interview, asking participants what changes they would like to make to their designs after seeing all the embedded designs in the playing video. Our participants then moved to the second phase of the study:

Full-motion mode: In this phase, the video play/pause button and video progress bar were available to participants. They could design on the playing video and simultaneously preview the data updates and all motion effects (moving swimmers, water splashes, ...). They could also stop the video, change their design, and restart the video again. We asked participants to continue to improve their previous designs and told them that they were free to add/remove/change data, designs, as well as their embedding parameters in any way they wished (with a playing video or without). Once they were satisfied with their final designs or 10 minutes had passed, they could submit their design. Similar to the previous phase, participants were allowed to finish the current ongoing design once they had reached the 10-minute mark. After submitting their designs, participants could again view a playable video of their final result via a sharable link that *SwimFlow* provided. Like in the previous phase, we asked participants to rate their satisfaction with their design on a 7-point Likert scale. We also asked to what extent they thought the final designs had improved and which mode they preferred to design in. We finally asked several open-ended questions on the design process in a second interview, with a focus on asking them to elaborate on their overall preference, what they had envisioned but could not do with the tool, and, more generally, to elicit feedback on missing features.

5.4.2 . Participants

As we set out to understand the impact of motion in the design process, we focused on participants with existing design experiences that could reflect on their process. We recruited them by advertising via mailing lists, through the network of authors, as well as through contacts mentioned by our participants. In total, we recruited 4 ♀, 3 ♂, and 1 gender-unspecified graphic designer. Participants reported their ages in 10-year bins from 18–54 years; 1 3 3 1 with most participants in the ranges of 25—44 years. They were either professional designers 5/8 or self-reported as "partial designers" (doing design work as a part-time job or having been trained as a designer previously). The non-professional designers were currently either visualization and human-computer interaction researchers 2/8 (including a design instructor) or students in design 1/8. They reported a high level of experience in graphic design (Table 5.3 1st row). Participants also reported using design tools and reading or creating visualizations frequently. We note that visualizations in motion and embedded visualization is a relatively new research

Table 5.3: Study with Designers. 1st row: Participants' self-reported design experience in years. 2nd row: The bars show participants' satisfaction before and after seeing the video in `motion-limited mode` as well as with the final design in `full-motion mode` on a 7-point Likert scale. 1: not satisfied at all; 7: extremely satisfied. 3rd row: Participants' responses on a 5-point Likert scale about to what extent `full-motion mode` improved their design. 1: not improved at all; 5: extremely improved. 4th row: Participants' preference between `motion-limited mode`, `full-motion mode`, and `non-preference` options. Red arrows: participants' satisfaction shifted in `motion-limited mode` AFTER seeing the video; Green arrows: participants' satisfaction increased with `full-motion mode`.

	P1	P2	P3	P4	P5	P6	P7	P8
Design Experience	>5	2-5	>5	>5	1-2	>5	2-5	2-5
Satisfaction								
BEFORE seeing video								
AFTER seeing video								
FINAL deisgn								
Improvement								
Full-motion Mode								
Preference								

direction in visualization [20, 113], and the topic is highly specific. Thus, there are, as of yet, no dedicated "embedded or moving visualization designers" in the labor market. Our participants, however, were qualified to design visualizations and have done so in various contexts before. All 8 participants involved in our experiment are professionals or formal graphic designers, 3/8 participants had over 15 years of designing experience, while another 2 participants had experience in design with motion factors.

5.4.3 . Results: Design Decisions Making

We report here the designs produced from our study and the analysis of the first interview.

Designs Produced & Changes Made: While the purpose of this study is not to critique the produced designs, we report a high-level summary as an overview of the features used.

In `motion-limited mode`, participants created 44 visualizations, from 4—7 per participant 4 7. The majority of the designs 31/44 were meant to be in motion and attached to `swimmers`, and the remaining 13 were meant to be attached statically to the pool. Visualizations in motion represented data from a part of data categories, including swimmer's metadata, speed-, distance, and record-related data. The most common data items were the swimmers' nationality and distance to the leader, both chosen 7× [3] and various representations of world, Olympic, or personal records as well as the current speed (5× each). Visualizations in motion were never represented with traditional charts but almost equally often with text (12×) and graphics (11×). Lines were used 8×. The static visualizations were very diverse. The only representation that occurred more than once was the swimmers' name 4/13. Text was the most frequently used representation type 8/13, followed by Graphics (4×) and Lines (1×).

In full-motion mode, participants embedded in a total of 48 designs, from 4—8 per person 4 8. The majority were in motion 30/48 and attached to swimmers. The remaining 18 designs were static and attached to the pool. Compared to the motion-limited design mode, visualizations in motion now came from all our data categories. The distance to the leader was clearly the most common representation 9/30. The number of nationality representations saw the largest drop from 7 to 4. Instead, participants added representations of predicted record breaks (3×). The number of text representations dropped from 12 to 8, while graphics became the most frequent representation type (12×) followed by Line (10×). For visualizations staying static on the screen, the most frequent representations were of metadata, specifically nationality and swimmer names (4/18 each). The order of frequently used representations for static visualizations was the same as in the motion-limited design mode: text was the most frequent (9×), followed by graphics (7×), and one chart and line representation each.

Designs contained 4 more representations in the full-motion mode than in the motion-limited mode. However, visualizations in motion embedded in the video decreased from 75% to 50% of the total designs because participants found their initial designs too overwhelming and reduced the amount of moving visualizations. 6/8 participants added one or more new representations in the full-motion design mode. Half of the participants removed 1–3 previously added representations. Of the existing designs, 3/8 participants changed their motion status (2 designs were made static, and 1 changed to in-motion). All participants adjusted visual encoding parameters for their representations during the full-motion design phase.

Reasons for Changed Designs: Based on the designers' interview responses, we explain the reasons behind modifications made to designs in full-motion mode.

Added representations: Six participants added representations for the following reasons: (a) to complete information, which no longer seemed to be self-explanatory after seeing the embedded visualizations change on the played video (e.g., adding a text annotation for the lines of distance differences to the current leader) (2 participants); (b) to compare between data items that had previously not seemed important; for example, one participant added a [:::] diving distance represen-

3 "×" stands for the word "times" here.

tation to compare with the distance differences to the current leader. Their goal was to see if a starting advantage could be maintained over the race (1 participant); (c) two participants found that they visually had more space to embed visualizations in the full-motion mode; and (d) two participants added more data due to a newly found personal interest.

Removed representations: Four participants removed representations. (a) One participant found that some data was not as useful as previously considered because it had been hard to imagine how data changed over time. For example, one participant found that only one was enough to be shown for national competition; (b) another participant found that some data would not change over the course of the race, so it was unnecessary to let it move with swimmers as it might distract the audience. The lap time, for example, updates only after one lap is completed; (c) two participants cited changed interests.

Modified representations: Representations were modified according to several characteristics.

- Encoding parameters: Two participants adjusted *encoding parameters*, in particular color and transparency. One participant had misunderstood the motion direction and had used categorical colors opposite to their intention (for speed up rather than slow down), which they then fixed. Another participant changed a color to one they felt fit better for the moving representations.

- Representation type: The use of `text` in full-motion mode dropped significantly. Three participants reported finding `graphics` to be more readable and easy to track than text under motion. Also, as some numerical data, including lap time, did not update per frame, designers felt the accuracy of text was not needed.

- Embedding location: Three participants changed the embedding locations of their designs. Two stated that they could not tell the swimmers' swimming direction from the still image. Thus, they put their designs in the wrong position relative to the swimmers. For example, they had planned to add national flags behind swimmers but put them in front instead by accident. One designer explained that they found it unnecessary to put the representations too close to swimmers as the motion trajectory of visualizations was exactly the same as the ones of swimmers. Thus, they could track and identify information even if there was a gap between visualizations and swimmers. Finally, one designer said that it simply seemed natural to modify the representation location to fit the video context better.

- Motion status: Three participants switched some representations' motion status. Two mentioned that their data did not change over time or based on the swimmers' position; thus, they did not have a good reason to let the representation move with swimmers. One participant commented that although metadata was related to the swimmer, situating it with the swimming pool was a better choice, as it would free the space around the swimmer for data to be updated in real time. One participant changed a static visualization to be in motion without giving a specific reason.

5.4.4 . Results: Design Mode Preference

Here, we first report on participants' shifts in satisfaction between design modes as well as design mode preferences (Table 5.3). We then, according to our second interview, explain in detail what led to the shifts in satisfaction and choice of design mode preference.

Shifts in Satisfaction & Design Mode Preference:
Half 4/8 of our participants decreased their satisfaction after seeing how their static design looked on the video. 3/8 designers reported similar satisfaction as before. Only one designer was more satisfied with their static design. On the other hand, almost all designers 7/8 were more satisfied with their design produced in the full-motion mode. When asked, compared with the designs from the motion-limited mode (after seeing the rendering video), to what extent their design had been improved with the full-motion mode, 7/8 of the participants stated that their designs were improved by 1–4 points, out of 7-Likert points. One participant declined to respond. More telling is the overall preference of the design mode: All designers preferred to design with full-motion mode.

Reasons Behind Satisfaction Shift & Design Mode Preference:
Shifts in satisfaction: In motion-limited mode, the four participants who decreased their satisfaction after seeing the played video mentioned the following reasons: (a) two did not recognize the correct moving direction and put visualizations in the wrong place; (b) one found that they had added too much text, which was hard to read while playing the video; (c) another designer complained that the motion effect did not match their expectation — the world record line was behind swimmers at the beginning of the race. This happened because the moving speed of the record line was calculated by dividing the total distance by the record time (as is done in the Olympics). Thus, the line moves at the average speed of the record keeper instead of their real-time speed, which can confuse audiences. The three participants who maintained their satisfaction commented that the played video largely matched their expectations, especially when seeing the motion effects matching with the moving entities in the video. Thus, they were not surprised or frustrated. The participant who largely increased their satisfaction said they were at first not satisfied with their designs before seeing the played video because the design method was totally different from what they were used to — sketching on a storyboard. They disliked the predefined visualizations and wanted to customize all visualizations by themselves. However, after seeing the video, they found the video "super cool" — all their designs had life and could move with swimmers or stay static on the swimming pool. They were so excited to see the rendered

video because it was largely beyond their expectation. Thus, they gave the highest satisfaction, not for the design, but for the rendered video.

In `full-motion mode`, the seven participants increased their satisfaction because they had the opportunity to manipulate their designs in the same context in which their final design would be used. They mentioned that the full-motion mode gave them immediate visual feedback, which encouraged them to polish their designs and helped them to match their designs to their expectations; much less mental effort was demanded of them, and participants appreciated that they no longer had to speculate about what designs would look like. The participant who did not rate their satisfaction explained that, without comparison, they did not know how to evaluate their satisfaction as they had never used a similar design method.

Design Mode Preference: We observed that designers played videos in the `full-motion mode` for two reasons: (1) to preview the designs they created on the video screenshots and (2) to change designs while the video was playing. The second case was the most common case. `full-motion mode` was reported as the preferred design mode for the following benefits:

- Motion identification: Five participants said that the `full-motion mode` helped them to identify the correct moving direction, select which data items to add, let them better choose where to put things, check the conflicts between visualizations as well as overlap with swimmers, and get more feedback.

- Accessibility to dynamic data updates: Five participants reported that in the `full-motion mode`, they became aware of the updating frequency of a data item, which helped them to assign the movement status per item and check how the corresponding visualization would change. Participants were able to identify and de-prioritise data items that were updated less frequently than expected (*e.g.*, lap time) and switched them either to static representations or to simpler visuals.

- Flexibility of motion control: Four participants mentioned that with the flexibility of pausing, they could polish their design in detail and check design behavior at specific moments, such as turning.

- Instantaneous preview: Three participants said that as a designer, they should understand and be certain about their design before publishing it to the public. Thus, it was important to be able to have a quick design-reflect-redesign phase — previewing the effect of their design and making modifications.

- Context awareness and confidence: Three participants also much appreciated directly editing in the same context as the final product, which gave them confidence about their design as well as the final artistic product.

- Expectation match: Two participants stated that it would seem natural to do manipulations directly on the video if they were asked to design things for a motion context.

On the other hand, `motion-limited mode` was commented on in almost the inverse way. Participants mentioned that it was hard to imagine the final product, that the mode led to misunderstanding of the swimming direction, that the design felt uncertain, unreliable, or confusing, and that it was hard to avoid conflicts.

5.4.5 . Results: Authoring Probe Improvement

According to the general comments left in the second interview, participants also requested additional functions for *SwimFlow*. A set of features they wanted were, unsurprisingly, related to the more flexible specifications of the visual encoding, akin to modern visualization authoring tools, which were too numerous to include in our probe. Some requests, however, were also related to the motion context and the situated visualization. Participants wanted some features akin to video editing tools that would allow them to select when representations would be visible. Others wanted visual effects like zoom-in/out or fade-in/out features to draw attention. Participants also voiced a wish for more data referents to which visualizations could be attached, for example, to place a visualization relative to another visualization's position.

5.5 . Discussion

Overall, we found that the full-motion design context, and in particular, the ability to see design changes reflected immediately with moving referents, was extremely helpful. Having the ability to play video and embedded visualizations together increased designers' satisfaction with their final designs. As such, it seems an important area for future work to develop prototyping and production tools for in-situ visualization in motion scenarios. Yet, several considerations arose from our work and the study results:

5.5.1 . Impact of Context-Coupled Design on Vis Choices

When we started our work, we expected that the moving context (swimmers, background) would affect the design experience, as most authoring tools usually start with a blank canvas. We began our exploration of designing embedded visualizations in motion using traditional mechanisms that involved sketching on transparent overlays that allowed participants to move visualizations over a background image [14, 193, 194]. We observed that when designing on such a static frame, even when movement could be simulated, it was hard for designers to imagine the potential change of movement of the referents and the dynamics of the data attached to them. We observed similar problems in the motion-limited context when designers used our probe on a static video frame. Often, issues with visualization choices (color, transparency) and their placement were only noticed when designers could preview their designs, the data updated, and the corresponding entities moved together.

This importance of having a playable video to design situated visualizations in motion is supported by the fact that all of the designers tweaked their visualizations, and more than half added/removed visualizations after seeing the video preview. Benefits of a video preview have been found in other tasks and contexts, such as turning visualizations on/off by audiences [50, 51]. Here, we are able to explain where benefits come from for designers. We saw, for example, that the availability of a full-motion design mode influenced the selection of representations. Some designers were reluctant to add multiple moving visualizations when designing with incomplete contextual motion and often added text as the simplest representation. Nevertheless, when they actually saw their completed design in motion with the referent, they felt that the visuals were more subtle than expected and that they could add more moving components. Designers also found that graphics were easier to track than text when they were moving. Thus, context-coupled design with complete motion effects impacted not just simple visual design choices (such as color or position) but also data representations.

Arguably, the most surprising outcome was visualization changes due to the data values themselves. While playing their designs in the video, several designers noticed that some data elements they considered important and were often attached to the swimmer were, in fact, not updating regularly or not as expected. Thus, designers decided it did not make sense to give them prominent positions, such as the regions around the swimmer, and either removed them or reverted to static visualizations. We plan to investigate in future research if these findings apply in other moving contexts, for example, in sports or games where trajectories are not necessarily as linear as in swimming.

While we found advantages to the full-motion design mode, we do not expect that a future tool inspired by our findings would necessarily replace traditional methods such as sketching for prototyping. For example, people could sketch a set of first ideas using their preferred method (paper-based designs, storyboards, video presentations, cardboard mockups, etc.) and then switch to a design tool to try them out and refine them. We can also consider intermediate prototyping approaches, adapting sketching methodologies to a motion context. We can envision sketch-based authoring tools that allow designers to directly sketch visualizations on videos. Existing sketch-based authoring tools (e.g., [182, 195]) can indeed combine sketching with data-binding. However, they need to be adapted to preview videos and to provide object and trajectory detection in order to help designers attach their sketched visualizations to motion contexts (like swimmers).

Summary: The study with our technology probe is a first exploration focused on how to *design* embedded visualizations in a motion context and, in particular, with visualizations that are meant to move with their referents. The most significant finding from the study is that it was important for designers to see the motion of referents together with visualizations but, very importantly, also to see how the visualized data updated with movement. While our probe only targeted the swimming context, we hypothesize that the importance of the full-motion mode will also hold for design environments that target other types of sports, in particular, if these other sports include very complex and dynamic types of movement. Yet, with other types of motion and contextual factors in other sports, a future tool might need dedicated features to address these complexities. The combination of sketching and full-motion contexts is an interesting future avenue for research on the design process for embedded visualization in motion.

5.5.2 . Tool Complexity

Our study was based on a technology probe, which, by design, is not a complete system but instead is meant to help envision what a *complete* visualization authoring tool for a motion context would look like. Specifically, participants expressed the need for visualization authoring features found in complete authoring tools such as Charticulator [33], Lyra [179], or Data Illustrator [178]. But they also requested features from full video editing tools, such as zoom in/out, fade in/out, control of timings, etc. In addition to these two sets of features, we also need to provide ways for designers to embed and anchor their visualizations to particular moving objects (as we do in our technology probe), assuming such objects are pre-identified. If they are not identified, designers also need to define trajectories for their moving visualizations. There may even need to be features to define the updating of dynamic data (like the current swimmer speed) as the video is playing: how often to update which data, how to highlight changes, etc.

As such, a very large number of functionalities are desirable to support the design of visualizations in motion. This large feature set invites the question of whether all features are essential for designing visualizations in motion. What are, in the end, the key features for such authoring tools to avoid overloaded interfaces and feature fatigue? Should one single authoring tool attempt to cover the entire design process, or is a multi-step design workflow more suitable (define the video/motion-related features in one tool and refine the visualization design details in another)? This remains an open question.

An added problem in the support of a design workflow is the requirement of an underlying video with associated tracking data. In our case, the tracking data was prepared semi-automatically in that some data was extracted automatically, and other data had to be annotated by hand. For example, we had no computer vision algorithm that could detect a swimmer's single stroke. Future tools will similarly have to rely on the availability of data or include possible manual annotation features. Systems such as iBall [57], for example, put a lot of effort into the development of a computer vision pipeline to track players and game information for embedding visualizations. When a future authoring tool needs to support multiple camera angles, positions, and movement, having tracking data synchronized and registered from all cameras becomes important. The tool complexity would further grow with the required need to detect or define perspective distortions of the scene so that visualizations can be embedded correctly.

Summary: We developed *SwimFlow* as a technology probe, and as such, it worked very well to elicit features of future technology to support design processes around embedded visualizations in sports videos. A big problem for fully-fledged tools will be the potential necessity to be visualization authoring tools, with video editing features, data tracking and editing possibilities, and new features for controlling how visualizations will be embedded in relation to the data referents.

5.5.3 . Guidance on Effectiveness

In our work, we used a user-centered design process (survey, workshop, testing with designers) to prioritize the data and the visual representations to include in our technology probe. There are many more possibilities in terms of data but also visual representations to support. These can be, of course, added if our probe was turned into a future prototype. One potential future feature our technology probe did not concretely surface is the potential need to provide designers with guidance on how best to design embedded visualizations in motion. For static visualization design, the community has a large number of design recommendations for how to best represent data for different tasks and contexts, and even recommender tools [196–198] and catalogs [199, 200]. Yet, it is unclear if our current understanding of how effective visualizations are still applies to motion contexts. As such, a future recommender system in this context would be based on little empirical evidence. Recent work [113] has started investigating the impact of motion on reading visualizations, but clearly, more work is needed to be able to provide concrete design recommendations for effective visualizations in motion.

Summary: In our study, we compared full-motion to a motion-limited design mode. The motion-limited mode is fundamentally the same as offering designers of embedded visualization a screenshot as a design prop to create visualizations on. This would be a low-cost design alternative that does not necessarily require videos or all tracking data - but could simply use authoring and embedding features. Our study explored to what extent having the full-motion mode would be useful and why. Specifically, we found that the full-motion mode led to more diverse designs, less mental effort, a faster design process, reduced uncertainty / more confidence about the final design, and more satisfaction. The full-motion mode allowed the preview of dynamically updating data and gauging the potential visual overload of multiple embedded visualizations in motion. Interestingly, participants also changed representation types when they saw visualizations moving. Text became much less commonly used, indicating the difficulty of imagining what representations might look like when in motion. Finally, previewing motion was important for several participants who had misunderstood movement direction.

5.6 . Summary

We investigated how to design visualizations that may be attached to moving contexts, such as swimmers in a race. We provide insights about what data and visualizations are a good fit for the swimming context. More importantly, we identified how the motion context can greatly affect the visualization design process and choices. We discussed the more general challenges and open questions in adapting existing prototyping and visualization authoring practices for video contexts and pointed to a vast space to explore on how to design situated visualizations in motion. There are many factors that need further exploration, such as various application scenarios in and outside of sports, different target audiences and their focus, the data, and, of course, the visualizations in motion themselves, among others. These remaining factors are related to the perception of embedded visualizations in motion that may eventually lead to guidelines.

6 - SITUATED VISUALIZATION IN MOTION STUDIED IN THE CONTEXT OF VIDEO GAMES: A SYSTEMATIC REVIEW AND AN EVALUATION

My perception studies (Chapter 4) demonstrated that people can read and get reliable information from visualizations in motion moving at high speeds and under irregular trajectories. These studies were conducted in a context-less environment, and reading visualization was the main and only task that participants had to complete. Yet, in real-world contexts, reading visualizations in motion is often no longer the primary task of viewers. Situated visualizations in motion are embedded into the context to improve watching/user experience, help people gain additional insights, and support their primary tasks. For example, in sports analytics, visualizations in motion are attached to athletes to provide dynamically updated race-related information (*e.g.*, potential shooting ratio and athlete's current speed) to audiences [51,57,58,187]. The audience's main mission is to watch the race rather than read the attached visualizations moving with athletes. Similarly, visualizations in motion are only intermittently checked in fitness tracking — people take a glance at their performance data (*e.g.*, heart rate and calories burned) from their fitness tracker, but exercising is their main in-context task [201]. Furthermore, in video games, in-game visualizations that are embedded close to the game characters (*e.g.*, a health bar [202] over a game character's head) aim to inform players of useful information to support quick decisions related to the game objective. Participants' main focus is on the game, as their target is to win.

As such, viewers need to read visualizations in motion and get helpful information from them in a busy context. Thus, understanding **how the context affects the design of *visualization in motion* as well as its user experience** is important.

> The following content is an updated version of my original article, which is under preparation and has not been published yet. The article was led by myself and co-authored with my supervisors, my co-advised Master student, and my collaborator: Federica Bucchieri, Victoria McArthur, Anastasia Bezerianos, and Petra Isenberg. In the following content, I switch from "I" to "we" to describe our work.

We selected video games as an investigation platform because video games have visualized dynamic data, busy context, primary game missions to complete, and rich motion factors. We first conducted a systematic review on situated visualizations in motion in video games. We then implemented a First-Person Shooter (FPS) game called RobotLife that allowed us to embed and study different visualization designs. Next, we ran **a lab study** with game enthusiasts to understand the impact of a concrete context, with primary tasks to complete, on visualizations in motion design as well as their user experience. We ended our work by providing considerations on trade-offs in designs of *visualization in motion* between the readability of visualization, the aesthetic fit to the context, the immersion the visualization brings, the support to the primary task the visualization provides, and the harmony between the visualization design and its context.

The systematic review on situated visualization in motion in video games and the implementation of RobotLife were done by my co-advised Master intern, Federica Bucchieri. The associate work was partially published in her EuroVis poster [203] and her Master thesis [170]. Thus, I excluded these two sections from my dissertation. Please refer to Section III and Section IV in the appendix for details about the classification of visualizations in motion in games and the technique development of RobotLife.

6.1 . Related Work

Apart from visualization in motion, our work is also related to situated and embedded visualization, especially with embedding locations of visualization, as well as visualization in video games.

6.1.1 . Situated and Embedded Visualization

An important criterion in many definitions of situated visualization [1, 21, 204] is *embedding location*. The way we consider embedding location in our work is tightly related to what White and Feiner [205] call locus of presentation and spatial relevance in their situated visualization framework. Willett *et al*. [20] formalized the difference between situated and embedded visualization by considering the relationship between data and data referents. In situated data representation, we find a relationship of spatial proximity. Embedded representation takes this proximity to the extreme by tightening the data representation with its referent. Our designs use these tight spatial connections, and we, therefore, consider them embedded representations.

Many applications of situated and embedded visualizations already exist using technology such as AR [51, 57–59, 97], mobile devices [98, 107, 108, 206], data physicalizations [43, 96, 207], or regular displays [52, 56, 60, 65]. We also refer to Bressa *et al*. [204] for a broader review of situations and situated visualizations. In our work, we focus, in particular, on the video game context. We made use of embedded visualizations by placing visual representations directly into the game world — closed to, overlapped, and integrated with game characters as the data referents.

6.1.2 . Video Game Visualization

Since our work uses video games as a real-world study context for visualizations in motion, we also reviewed relevant work on visualization use and design in this domain.

Zammitto [208] analyzed how video games provide the player with important visual information through techniques such as silhouettes, mini-maps, Head-Up displays (HUDs), or Fog of War [209]. The author stressed the importance of reviewing visualizations by genre. We took this advice into account in our review [208]. Bowman *et al*. [210] presented a framework of five categories including primary purpose, target audience, temporal usage, visual complexity, and immersion/integration to classify any video game visualization; Following this classification, the designs used in our study focus on status information as a primary purpose, for the player themselves, with visualizations continuously present, with basic visual complexity to be readable at a glance, and an immersive/integrated (situated) design.

Other research targeted specific visualizations and their effectiveness. Brooksby [211] in his exploratory study about representation of health in video games, identified five categories of health representations: mobility, ability, psychology, social and pain. Unsurprisingly, the most frequent depiction of health appeared to be pain. Peacocke *et al*. [212] studied players' performances with various types of displays. Most closely related to our work is their study of three health visualizations: a bar, heart icons forming a bar, and blood splatter. All three were compared as a HUD display and a diegetic[1] design. Diegetic designs are most closely related to situated visualizations although the latter do not have to be available to a game character. The results showed that participants favored the HUD variants and that around half of the players found the diegetic designs to be a hindrance to their game success. Gittens and Gloumeau [214] also analyzed health visual representations, exploring the impact of segmented health bars on players preferences for a game. Their results showed that the majority of their players preferred segmented bars over a single bar design. Despite these results, we did not use segmented bar charts since our embedding locations were different and segmentation would have been too unusual for two of the three designs we evaluated. In his work on information visualization in games, Karlsson [215] also stated how important colors are to distinguish enemies from allies in FPS games and Massively Multiplayer Online Role Playing Games (MMORPG). Horbiński and Zagata [216] studied symbols on the map of the *Valheim* video game [217]. Inside the game map, different interactive elements (mainly locations and objects) were represented by pictographs to inform

[1]Game elements are diegetic if they exist within and are consistent with the fiction of the game's world (e. g. the player's character perceives them and the player responds to them as such). Elements are not diegetic if they exist for the player, but not for the characters (e. g. most of the HUD or third person perspective information) [212, 213]

users about the game. Since *Valheim* is a survival game, understanding the meaning of each symbol was crucial for the players.

More generally, many studies on player experience have been conducted [211, 216, 218–220] in video games research. Prior work, for example, contributed an analysis of factors that contribute to videogame playability as viewed by players. In particular their factor "game entities" and their metadata relates to our work as common data referents. Other work considered what players look at in video games. El-Nasr *et al*. [221], for example, showed that in FPSs players focus on the center of the screen whereas they looked around more widely in Adventure games. Martinez *et al*. [222] studied color and found a correlation between game type and the color used. We decided to use bold colors such as turquoise, light green, and yellow for the ambient light of our video game to convey excitement and allow for a good contrast between the visualization and the ambient colors.

Motion characteristics have also received researchers' attention. Milam *et al*. conducted video game studies about visual designs with motion involved. They investigated the effect of motion attributes, including flicker, shape, speed, and repetition, on the perception of visual complexity [73]. The authors explored designs of game elements, such as a boss character, a background ring, and a visual feedback explosion, by adjusting visual features, such as size, speed, and density [223]. They also evaluated these visual features with players with different expertise levels [224]. Instead of focusing on visualization, the work from Milam *et al*. mainly focused on the impact of game element designs on gaming experience or the effects of gaming expertise on game performance. More recent work from Dillman *et al*. [225] investigated how visual interaction cues such as an augmented arrow can indicate to participants where to look and go in the game context. What has been less frequently researched is the impact of *visualizations in motion* on user experience in a real-world context such as games. Our work specifically focuses on this challenge.

6.2 . RobotLife: A Test Platform for Visualizations in Motion

Our systematic review of visualizations in motion in video games (Section III in the apendix) shows the current visual data representations, the embedding locations of visualizations, and the data encoded by visualizations are various. To investigate how visual representations, as well as their embedding locations, might affect user experience in the game context under motion, an environment that allowed us to collect game data was required. We, thus, developed our own video game RobotLife — an FPS game. We chose FPS as our target game genre because (a) FPS is a motion-prone game in which both the movement of game characters and camera perspectives can happen, and (b) FPS is a popular game genre [226]. As such, we were confident that we could find experienced players for our user study.

The technique development of RobotLife can be found in Section IV in the appendix. I next describe the storyline of RobotLife to help readers understand our study task.

6.2.1 . RobotLife Storyline

RobotLife is set inside a robot factory. A virus infiltrated the factory and altered some robots. The altered robots became evil and started damaging the electric system of the factory. The player acts as the guardian of the factory and has the duty to eliminate all evil robots. This task comes with a main challenge: distinguishing the evil robots from the good ones. The evil robots are acting secretly, trying not to be recognized while destroying the factory. The virus gave extra health to the evil robots, so they come with more health with respect to the good robots. Our game's design of health value is different from that in commercial games, as we wanted players to pay attention to the visualization instead of acting by inertia. The robots are not dangerous for humans, but every robot comes with a life-saving mechanism, so when attacked, they fire back immediately. The central management system of the factory spotted 8 evil robots connected to the electrical system of the facility. The player wins the game when all the 8 evil robots are eliminated, and not more than 2 good robots were damaged. An evil robot can never become a good one. The level map was designed to be linear but, at the same time, challenging and big enough to support navigation without information overload. Some areas of the map encourage players to jump between platforms or over decorative objects, with the aim of creating extra motion factors in the gameplay.

6.3 . An Evaluation with Game Enthusiasts: Study Design

Our main goal was to explore how players would experience situated visualizations in motion inside a busy real-world environment that required a primary task: primarily navigation or shooting. To understand player experience, controlled experiments with simple and short tasks are not the right choice, particularly here, because the actual gameplay is almost impossible to control. Instead, we designed our experiment around qualitative reports of player experience and quantitative measures on Likert scales. Our evaluation is pre-registrated at `https://osf.io/h4cks`. A user study demonstration video can be found at `https://youtu.be/I7sD-IQlOZM`.

6.3.1 . Visualization Design and Representation Selection

In our systematic review of visualizations in motion in video games (Section III in the appendix), visualizations in motion most often depicted quantitative data and single-dimensional health values. As such, we implemented different visualizations of health for each robot.

In our systematic review (Section III in the appendix), we found that to maintain global harmony between the game characters, the widgets attached to the characters, and the game environment, the in-game visualization's embedding locations and

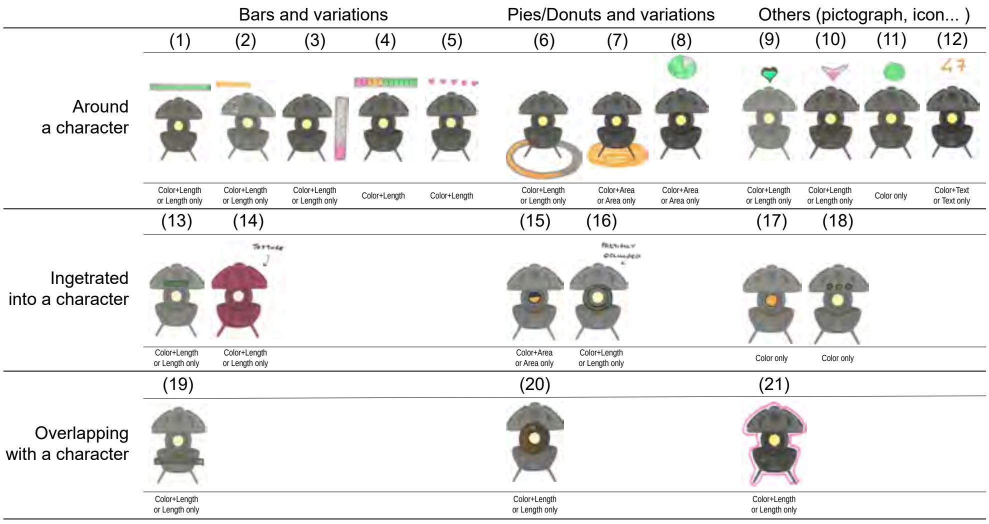


Figure 6.1: Health visualizations considered using different embedding locations, colors, and types of encoding. Other design variations are easily possible for Rows 2 and 3 by using ideas from Row 1. These were not explicitly drawn out.

its visual representation cannot be discussed individually. Choosing an embedding location has an impact on what type of encodings are possible and sensible. For instance, a health bar is typically put over the head of a character instead of at the feet of the character. In the design of our hover bot health visualizations, we, therefore, chose the integration level of visualization to its data referent as the main varying factor. The integration level is composed of the visualization's embedding location and its visual representation. The embedding location, *around* a game character, *integrated* into a game character, and *overlapping* with a game character, can have a direct impact on how viewers see and experience the visualizations themselves in terms of aesthetics, immersion, and readability. For example, displaying a visualization around the character increases the visibility of the character itself, providing an indicator of its position but letting the visualization artificially stand out. Embedding a visualization in the character design (integrated) impacts the character's aesthetics by altering its original design and may be less readable. Visualizations overlapping the character are more prone to occlusion due to other objects in the game scenario.

Fig. 6.1 shows the visualizations we considered, presenting different combinations of the embedding locations, visual representations, colors, and types of encoding. This initial set was inspired by our systematic review (Section III in the appendix), but certainly, more variations are possible by choosing other colors, offsetting visualizations in space, and changing encodings. In lieu of constructing a nearly endless set of possibilities, we focused on this set of 21 options as it already gave us a good diversity of integration levels. From pilot testing our game, we found that a

Figure 6.2: Three visualization designs illustrated in the context of our game RobotLife: (a) `Non-intergrated design`: a bar chart positioned outside of the game enemy character; (b) `Fully-integrated design`: a bar chart integrated into the texture of the game enemy character; and (c) `Partial-match design`: a donut chart matching a part of the shape of the game enemy character.

reasonable completion time for our final study allowed us to test three designs per participant within-subjects. To choose these three designs, we prioritized designs we saw in actual video games as well as readability in our specific game world. We also chose designs such that they required the same type of visual inference: the reading of length, which was one of the most common encodings in our systematic review.

We excluded Designs 8, 12, 19, and 21 from Fig. 6.1 because we did not see them implemented similarly in any actual games. We could not use Designs 6 and 7 embedded below the character because the robots floated, and the distance from the ground could be confusing for players. We also excluded Design 16 due to the partial occlusion caused by the robot's design. We considered Designs 10, 13, 15, 17, and 18 too small to be quickly readable. We excluded Designs 9 and 11 as primarily categorical encodings. We finally chose Design 1, a typical bar over the head of the game character, as a  `non-integrated design`. Design 3 was a close contender but the horizontal bar chart was the most typical design in FPS games. Designs 2, 4, and 5 are variations of Design 1, but our final design is closest to Design 1. We also chose Design 14 as a  `fully-integrated design`. Design 20 became the final design as it represented a  `partial-match design`. Design 16 is a variation of 20 with simply a thinner donut ring. The in-game implementation of our three stimuli is seen in Fig. 6.2.

6.3.2 . Main Task and Study Variables

To win the game, participants had to identify and kill all 8 evil robots. Participants would lose the game if they hit more than 2/16 good robots, even if they did not kill them. Good robots had a health level lower than 66%, while evil robots had a health level higher than 66%. The rule of not-damaging the good robots was intended to avoid participants shooting blindly at every robot, having in mind only the main goal of killing the 8 evil robots in the scenario. Each robot showed one of 6 percentages: 18%, 32%, 43%, 58%, 72%, and 83%. We chose those percentages to be the same as the ones used by Yao *et al*. [113] in their evaluation of the readability of moving bar and donut charts. To eliminate learning effects, each percentage value was randomly assigned to one of the 24 robots on the floor. Therefore, every robot had a different health value at each iteration of the game.

6.3.3 . Procedure

The study was conducted in the lab, with a DELL U3014t display (refresh rate at 60Hz), a Dell XPS 8910 desktop with an NVIDIA GeForce GTX 730 graphics card, a DELL KB216t keyboard, and a DELL MS116t1 mouse. The study was a within-subjects experiment with participants testing all three designs. During the initialization phase, participants filled out a pre-questionnaire about their demographics, their gaming experience and familiarity with actions on PC. Using a 7-point Likert scale, we asked participants to self-evaluate their proficiency or skill in (a) playing video games and (b) playing video games on PC by using a mouse and keyboard as input devices. We also asked which types of video games participants usually played. Furthermore, we asked participants to report their gaming frequency regarding (a) playing video games in general, (b) playing FPS games, and (c) playing games on PC.

Participants proceeded to a tutorial in which they learned how to play the game and how to read each visualization. Next, participants completed the three conditions. Condition order was assigned using a Latin square. Each condition block included a training and a trial phase. In the training phase, we asked participants to do proportion estimations in a static context (the shown robot did not move). Participants had to identify if the displayed robot was an evil one or a good one. Participants had to succeed at least 6 times to move toward the trial phase but could do as many training trials as they wanted. In the trial phase, the gameplay consisted of playing RobotLife for a duration of 5 minutes. Participants were free to play the game as many times as possible according to their capabilities. Specifically, if a player died or won before 5 minutes, they had to start again and play until 5 minutes were over. After the timeout, an in-game questionnaire was automatically presented that asked about aesthetics using the BeauVis scale [227] and additional Likert items related to readability. After submitting the answers to the in-game questionnaire, a new training-trial block started. After all three blocks were completed, the study ended with a post-questionnaire as well as short post-interview.

In the post-questionnaire, we asked participants to rank the three visualizations according to how: (a) easy they were to read while in motion, (b) well they fit into the aesthetics of the game, (c) well they support the mission, and (d) supportive they were for a positive overall game experience. Participants had to explain the reasons for their ranking. Finally, we conducted an interview with participants where we asked: (a) how motion factors (including the movement of robots as well as the movement of players) affected their gaming performance, (b) how contextual factors, such as busy background and lightning, affected their gaming performance, (c) their strategies to read visualizations under motion, and (d) general comments about our study.

	1	2	3	4	5	6	7
Overall video games	0	0	0	1	11	5	1
PC gaming experience	0	1	0	2	8	6	1

(a) Self-evaluate proficiency in game playing. 1: Novice, 7: Expert.

FPS	Platformers	Action/ Adventure	RPG	TPS	Sport games	Puzzle games
15	6	12	14	9	2	11

(b) Self-reported types of video games participants usually play.

	Once every few years	Once or twice in a year	Once or twice in six months	Once or twice a month	Weekly	Daily	MEDIAN	MODE
Video games in general	0	0	1	1	5	11	Daily	Daily
FPS games	1	1	2	4	7	3	Once or twice a month	Weekly
PC game playing	0	2	0	1	6	9	Weekly	Daily

(c) Frequency of playing video games in general and FPS games, and on PC.

Table 6.1: Gaming experience, games familiarity, and experience in playing games on PC of our participants in formal study.

6.3.4 . Pilot Study

In order to thoroughly test our study, we conducted a pilot with 12 participants who were not specifically game players (self-evaluated proficiency in game playing on overall video games: $M = 3.83/7$, $SD = 1.34$). Pilot details and results can be found in the associate Master thesis [170]. We contrast the results of this pilot to our formal experiment where it is interesting.

6.3.5 . Participants

We looked for participants via university mailing lists and hanging up flyers in university buildings. Following our institute's payment policies, participants received no remuneration in cash. Instead, we offered boxes of chocolate of equal value. In total, we recruited 18 game players: 2 ♀, 16 ♂. Participants reported their ages from 18–44 years: 5 12 1, with most participants in the range of 25–34 years. Our participants had high gaming expertise ($M = 5.80/7$, $SD = 0.69$) and were skilled with gaming using a keyboard and a mouse ($M = 5.17/7$, $SD = 1.10$) (Table 6.1a). The majority of our participants 15/18 usually played FPSs (Table 6.1b). Overall, all our participants were video game enthusiasts, over half of them had a high FPS gaming expertise, and the majority of them frequently play video games on PC (Table 6.1c).

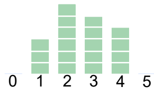
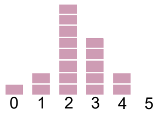
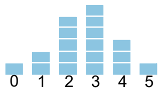
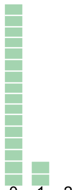
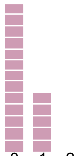
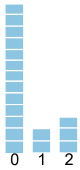
			
Total number of evil robots killed	457	432	486
Total number of won games	46	41	47
Distribution of how many participants won how many times	 0 1 2 3 4 5	 0 1 2 3 4 5	 0 1 2 3 4 5
Total number of lost games	2	5	8
Distribution of how many participants lost how many times	 0 1 2	 0 1 2	 0 1 2

Table 6.2: Study results of participants' game performance. Height of the bar chart: number of participants who won/last. : `Non-intergrated design`, : `Fully-integrated design`, : `Partial-match design`

6.4 . An Evaluation with Game Enthusiasts: Study Results

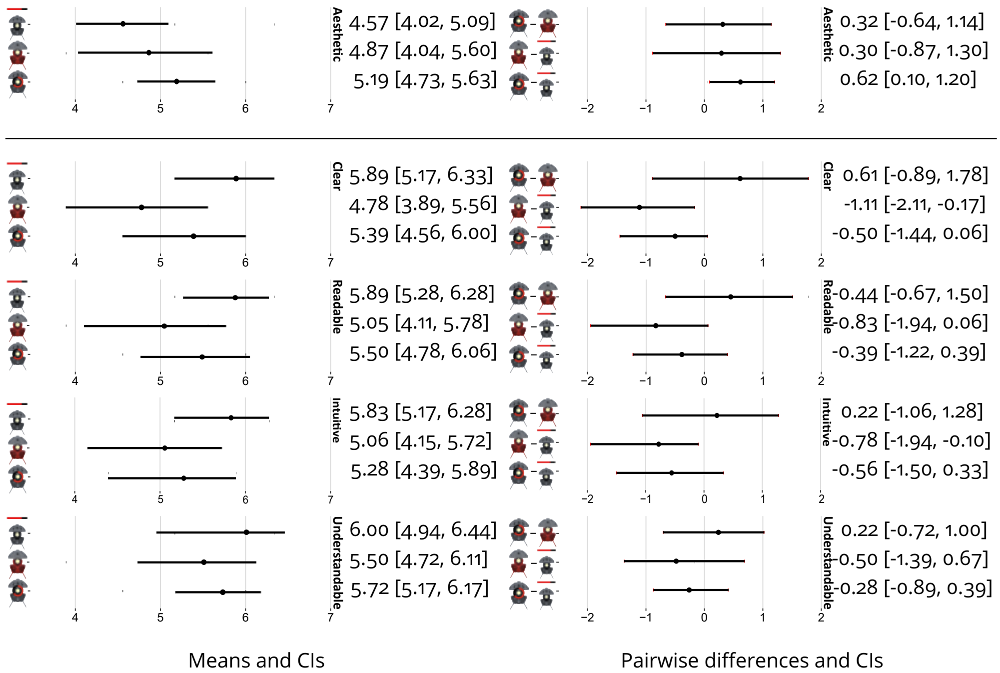
We report our results on gamer experience under three main aspects: (a) participants' perception experience regarding readability and aesthetics of visualizations, (b) their visualization design preferences, and (c) their responses to the post-interview.

Before engaging in deeper analysis of participants' experiences with visualizations in motions in the game context we analyzed overall gamer engagement. We conducted this analysis to see how seriously participants were about succeeding in the game. The overall performance of our participants, which relied on reading the visualizations, was extremely high. The majority did not lose a single time in all conditions — ■■■□ 16/18 participants did not lose at all with the `non-integrated design` and ■■■□ 13/18 did not lose at all with the `fully-integrated design` and the `partial-match design`. The counts and distribution of participants' performance are represented in Table 6.2.

6.4.1 . Statistical Analysis on Aesthetic of Visualization Designs and How Well Visualizations Could be Read

In order to better understand the influence of the different designs on experience we analyzed how readable and beautiful participants considered them to be.

Table 6.3: Detailed results of statistical analysis. Top: Mean and pairwise differences between conditions of the Likert scale on aesthetics. Bottom: Means and pairwise differences between conditions of four Likert items on readability. Error bars represent 95% Bootstrap confidence intervals (CIs) in black, adjusted for pairwise comparisons with Bonferroni correction (in red).



Readability and aesthethics are important components of visualization experience. After the end of each block of trials participants rated each design using a Likert scale.

Measuring Aesthetics: We used the 7-point BeauVis scale [227] as our questions. BeauVis is a validated scale to measure the aesthetic pleasure of a visualization. As such, we report a single aesthetics score (Table 6.3: Top).

Measuring Readability: There is no validated scale to assess the readability of a visualization so we used a set of common terms in the visualization literature to approximate the measure. Participants rated how *Clear*, *Readable*, *Intuitive* and *Understandable* each visualization design was on a 7-point Likert scale. We report results for each Likert item in Table 6.3: Bottom.

We report means and 95% confidence intervals (CIs), which means we are 95% confident that this interval includes the population mean. We also report the CIs of mean differences to compare different conditions. CIs have been used in Likert scale analysis in previous visualization research [228, 229]. We constructed all CIs using Bias-Corrected and accelerated (BCa) bootstrapping (10,000 bootstrap iterations).

We analyzed the CIs using estimation techniques. We interpret the CIs as providing different strengths of evidence about the population mean, as recommended in the literature [163, 230, 231]. When reading a CI of mean differences, a non-overlap of the CIs with 0 is evidence of a difference, corresponding to statistically significant results in traditional p-value tests. Equivalent p-values can be obtained from CI results following Krzywinski and Altman [166]. Detailed means, differences between conditions, and CIs of our analysis can be seen in Table 6.3.

We found the highest mean for aesthetics for the `Partial-match design`, followed by the `fully-integrated design` and the `non-integrated design` came last. We found evidence that the `partial-match design` was, on average, more aesthetically pleasing than `non-integrated design`. There was no evidence of other differences. We found evidence of a difference in how *Clear* and *Intuitive* visualizations were. In both cases, there was evidence of the `non-integrated design` ranked higher than the `fully-integrated design`. We found no evidence of a difference in ratings on how *Readable* nor how *Understandable* visualization designs were.

Summary: Participants considered the `partial-match design` more aesthetically pleasing than the `non-integrated design`. Yet, the `non-integrated design` had trade-offs regarding clarity and intuitiveness as it scored higher than the `fully-integrated design`. We found no further evidence of differences.

6.4.2 . Rankings of Visualization Design Preference and Considerations Behind Rankings

In the analysis of aesthetics and readability, tradeoffs emerged between the different visualization designs. We attempted to understand if these tradeoffs led participants to general preferences for certain designs. We also asked follow-up questions to understand the nature of potential preferences with a particular emphasis on understanding the influence of the motion context. Next, we report the ranking of the visualization design preferences asked about in the post-questionnaire and the reasons behind it. The following subtitles and emphasis are the same as the questions we asked. The complete distribution of rankings can be seen in Table 6.4.

How easy were visualizations to read *while in motion*?

Ranking Results: 10/18 participants chose the `non-integrated design` as the most readable design under motion. The votes for the `non-integrated design` were over three times higher than for the `fully-integrated design` and twice higher than for the `partial-match design`. The `Fully-integrated design` was ranked by 7/18 participants in the last place and commented on as the least readable design while in motion.

Our participants explained their rankings as follows:

(a) Design Familiarity: Participants explained that the `non-integrated design` is a typical design in FPS, and as such they were used to it and familiar with its location — no extra effort was needed to identify where the visualization was.

(b) Rich Experience: 2 of the 10 most highly skilled FPS players said that they could make extremely fast estimations with the `non-integrated design` because they were well trained and could ignore the motion effects. Even in commercial video games with overcharged context and complex tasks, they still had the capacity to make a quick and accurate estimation without actually reading the exact health values.

(c) Recognition Strategy: Participants reported that the `non-integrated design` could be used as a visual indicator to find the target robot while the other two designs could not, specifically when the robots moved around and crowded in the same area. This was due to the location of the visualization above the data referent.

(d) Integration Level: Participants stated that they had to be very careful about their judgments on the `fully-integrated design` due to the dynamic design of robots — sometimes the robot became shorter and sometimes taller. As such, the robot could be deformed, and its entire height could be inconsistent. These motion effects added additional difficulties to participants' estimation with the `fully-integrated design` as this visualization is fully coupled with its data referent.

How well did visualizations fit into the aesthetics *of the game*?

With the BeauVis [227] scale we measured the aesthetic of the representation itself, outside of its embedding context. Yet, in real application scenarios, the harmony between visualizations and their context is perhaps as important as the overall design itself. Thus, we specifically asked participants how well the design of our visualization fit the overall game context.

Ranking Results: Half of the participants 9/18 stated that the `fully-integrated design` best fit the gaming environment, while the remaining half put the `fully-integrated design` in the middle and last places. The `non-integrated design` was ranked as the least aesthetic one in the game context by 10/18 gamers. Over half of the participants 11/18 put the `partial-match design` in the middle place.

Our participants reported their choices as follows:

(a) Integration Level: Participants reported that the `fully-integrated design` was more realistic and immersive because it was fully coupled with the robot's design. In contrast, the `non-integrated design` and `partial-match design` were reported as less immersive and somehow artificial due to how they visually separated and floated above or in front of the data referents.

(b) Design Interference: Participants who disliked the `fully-integrated design` had opposite comments: for them the full integration broke the design of the game character itself, especially when the proportion was extremely high — the entire robot looked red, which annoyed them. Participants preferred to see the game skin and attached features because, in prevalent commercial games, game characters are always well-designed and decorated and, as such, players want to enjoy seeing them in their intended design.

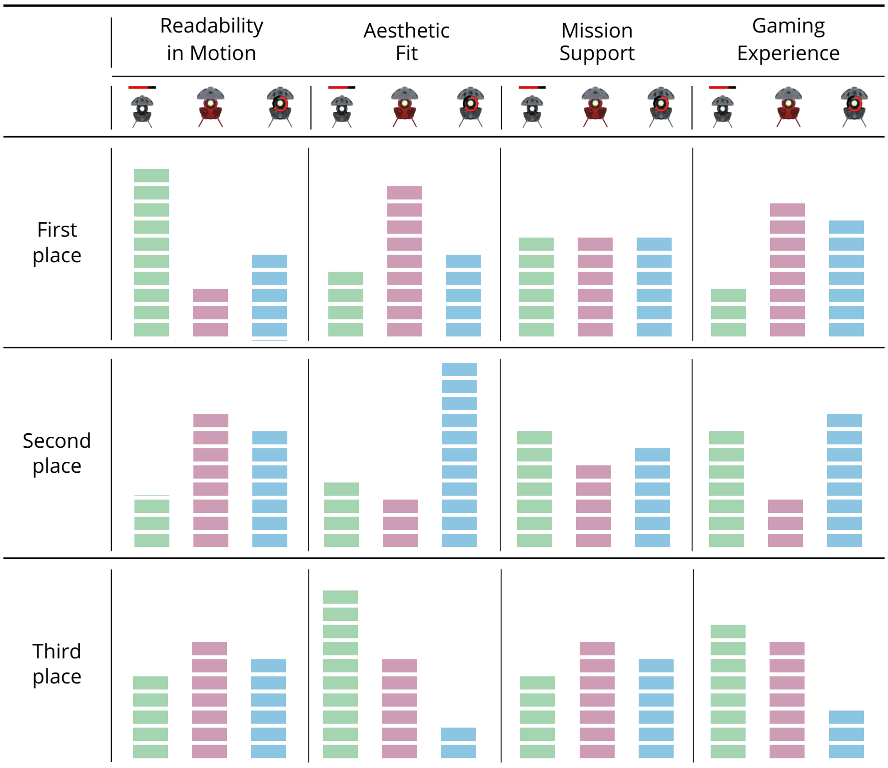


Table 6.4: Study results of participants' rankings on visualization designs preference. Height of the bar chart: number of participants who ranked. : `Non-intergrated design`, : `Fully-integrated design`, : `Partial-match design`

(c) Trade-off Selection: Participants selected the `partial-match design` as a trade-off — more realistic than the `non-integrated design` but also more artificial than the `fully-integrated design`. The `partial-match design` was floating in front of the eye of the robot and thus matched the character design. Participants said they would be excited to see new visualization designs, which are more immersive than typical ones, but also would like to preserve the possibility of appreciating the art of the game.

How well did visualizations support *mission completion*?

Ranking Results: The three visualizations were tied according to votes for first place with 6/18 votes each. For the middle and last place, the difference between votes was never more than 2. Specifically, the `partial-match design` got fairly equal votes for each place.

Our participants ranked the designs according to the following aspects:

(a) Task Orientation: 13/18 participants explained that as their mission was shooting at the evil robots, the task completion was heavily based on the percentage reading results. Thus, they answered the same way they answered for the question *"How easy were visualizations to read while in motion"*.

(b) Trade-off Selection: The remaining 5 participants shifted their ranking order as they were "trying to find a balance between easy-to-read and aesthetic-fit."

How did visualizations support a positive *overall game experience* (the game was fun, engaging, immersion, ...)?

Ranking Results: The `fully-integrated design` received the most votes (8/18) in the first place but also a lot of third place votes (7/18) for the gaming experience, while the `non-integrated design` was voted last most often (8/18). The majority of participants (15/18) put the `partial-match design` in first or second place.

Our participants chose their preferences based on the following aspects:

(a) Aesthetic-fit: 9/18 participants answered this question the same way as for the question *"How well did visualizations fit into the aesthetics of the game."*

(b) Trade-off Selection: The remaining half of the participants shifted their rankings — by trading off readability under motion and aesthetic-fit with the context.

(c) Immersion: The 3/8 participants who put the `fully-integrated design` in the first place said that they had never seen a representation that was directly integrated into the game character before. It was very exciting for them to see a new design in a video game, even though some participants did not perform as well in the `fully-integrated design` as they did in the `non-integrated design`, but they said that more training might improve their performance. Participants gave similar answers for the `partial-match design`: 7 participants appreciated the `partial-match design` because it fit the character design as well. However, 3/7 participants expressed their concerns about the suitability of the donut chart for other game character shapes. The other 3 participants reported that compared to a linear chart, they were not used to reading a circular one. Thus, for them, the `partial-match design` was, in fact, a challenge. Interestingly, 2/3 participants also expressed that they liked a challenge and preferred to play a challenging video game rather than an easy-to-win one. Most participants commented the `non-integrated design` was a "boring" visualization since it was too typical in video games.

Summary: The three designs for visualization-in-motion elicited different types of experiences. The `non-integrated design` was familiar to many players and they found them easily readable under motion; yet at a tradeoff for overall gaming experience for which it was ranked last. The `fully-integrated design`, on the other hand, was considered less easy to read under motion compared to the other two but gave the best overall gaming experience and aesthetics in the game environment. It became clear from the explanations of participants that integration of the visualizations in the environment, readability under motion, aesthetics, and overall experience with the game are all intertwined. Participants tried to find a balance between the readability of the design in context, the immersive experience the design provided, the innovation of the design, the game challenges the design brought, the task completion the design supported, and the harmony of the design in the context of the game.

6.4.3 . Features that Affected Game Experience

In our final interview with participants, we wanted to find out how the motion affected their experience of the visualizations as well as the busy real-world context of the game. We qualitatively analyzed the interview responses through open coding.

Motion Factors: Our participants explained how motion factors affected their gaming performance relating to the movement of each participant's game character as well as one of the robots.

Game Character movement: 4/18 participants stated that they needed to stop navigating in the game or slow down to read the proportion accurately, especially when the value was near 66% (the percentage that needed to be exceeded for a robot to become a bad robot). Two mentioned that the need to stop reduced their performance as they could not make quick decisions.

Enemy Movement: The autonomous movement of robots was mentioned as problematic by only two participants who complained about the deformation of the visualization. Two other participants reported that due to the robots' movement, their viewing angles on the visualization changed, which made reading challenging, especially when the visualization was not a traditional one (such as the bar) and the robot was rotated. Seven participants reported to play FPSs a lot and were used to the moving characters because motion is common in video games. Thus, they were not impacted by the robot movement.

Contextual factors: Over half of our participants 11/18 stated that they did not pay attention to contextual factors such as the busy background or the lighting, as they are typical parts of video games, and they were familiar with them. They reported to ignore them and only focus on the task. The others talked about color and lighting conditions.

Color: 4/18 participants mentioned to appreciate the high color contrast between the target (red charts) and background (dark green) which helped them to identify the robot quicker and complete the task faster. No participant mentioned the difference in color intensity for the `fully-integrated design` that arose due to the overlay over the robot texture.

Lighting: Only one participant mentioned that they focused on the rendering of the robots' skin, especially for the `fully-integrated design`. Due to the lighting, the rendering led to slight color changes from different views which the participant found to be distracting.

Reading strategies: As mentioned above, here, participants also stopped or slowed down their navigation to read the visualizations. Almost all participants 17/18 reported that they found a *visual referent* to estimate the 66% better. The defined the visual referent as a specific fixed position on the game character. Examples included the robots' eye position or specific locations on the eye or specific lines on the texture of the robot. This finding echoes prior work for reading bar and donut charts in motion where participants reported "dividing a chart into several parts" [113]. Two participants reported that when they saw a percentage close to 66%, they would leave the robot and move around to find other robot to compare to before making a decision.

6.4.4 . General Comments

10 participants left general comments for us. Nine commented that our game was really cool, extremely fun, and "super well" made. The study was interesting and a bit challenging, specifically under the `fully-integrated design` condition. One participant who works in the video games domain mentioned being encouraged to start thinking about trade-offs between immersive and informative designs for video games.

6.5 . Discussion

We next discuss our findings and implications for the use of visualizations in motion in a real context, both in terms of what choices designers have made (our systematic review (Section III in the appendix)) and how such choices affected user experience (our study). Many of our findings point to future work in the space of visualization in motion more generally but also in video games.

Visualization in motion design: Standards, diversity, and simplicity Our systematic review revealed many instances of visualizations in motion in video games. Quantitative and qualitative data were mainly represented by bar charts (often health bars) and text labels; categorical data was represented by text labels or signs. As such, visualizations were simple or replaced by text and also often showed just one data dimension. Past work on visualization glanceability [232] (but not under motion) showed that text was harder to read at a glance (compared to bar or donut charts), a context that is similar to how quickly gamers need to sometimes make decisions. This begs the question: Are bars and text an expected standard in games, or are game designers reluctant to add different visualizations because they are unsure how they will perform and be received by gamers? Is text perhaps less effective than expected in this context as well?

Most likely, these visualizations are now almost standardized in games, given that they are less prevalent in other contexts. Sports analytics is also a domain that contains dynamic updating data but bar and text visualizations in motion are not as widespread as in video games. Instead, often radial (bar) charts or donuts appear around the feet of players [57] or lines connecting players or indicating target records [187, 233] appear on the field and move with athletes. These subtle differences in representations, as well as data types between games and other real-world contexts, raise another interesting question: To what extent can the design lessons and common practices learned from one context be applied to another? Further investigation of specific real-world contexts can help determine if, as a visualization and design community, we should consider guidelines for visualizations in motion depending on data type as we do with traditional visualizations, based on the real context the visualizations will appear in, or (most likely) both.

Hard-to-read visualization: Visibility and blending in context In video games there are several situations when readability of visualizations may be compromised due to movement. For example, overlap between moving game entities, such as multiple characters (and thus their attached visualizations) is common. Moreover, a very subtle visualization design may blend too much into the background, so much so that it is no longer visible, or at least less visible than explicit representations that visually pop-out. Unfamiliar and harder-to-read visualizations, such as the `fully-integrated design` led to the worst performance for our experienced players. Nonetheless, visualization readability may not always be the desired outcome. Some participants mentioned that the `fully-integrated design`, while being least readable, felt more immersive and fit the game better. Some participants even stated that they found the `fully-integrated design` to be more challenging than other visualizations, but that they liked a challenge. Game design clearly takes into account the trade-off between ease-of-use and challenging-play. And previous research indicates that hard-to-use interfaces more generally, can improve the user experience in the form of feeling accomplished and providing higher value to the end-results produced from their use [234]. Our results indicate that game design needs to also consider the trade-off between creating readable vs. challenging in-game visualizations. The balance to strive for likely depends on the nature of the game and the player's personality. But it is worth considering if different levels of visualization readability could be integrated into the general notion of "difficulty levels" in games: the higher the difficulty level, the more challenging to read (but well-integrated), the visualization may become.

This notion of integration at the cost of readability is relevant to other real-world contexts where visualization reading is not the primary task and exact reading might not even be as important. It remains an open question to determine to what extent users are willing to compromise readability/visibility, how that affects (if at all) their primary tasks, and, more generally, how to improve visualization perception in such visibility-limited situations. We can expect, for example, that when watching a sport, visualizations should not distract from the event and the view of the athletes. As such, aesthetics and the immersion of the visualization might be as important as it was for the overall gaming experience in our study. Nevertheless, the opportunities of providing progressive/increasing integration or even making visualization reading more challenging on purpose is clearly game-centric and not necessarily applicable to other real contexts such as viewing sports where viewers do not seek a challenge.

Naturalness of motion: Several (well-trained) players mentioned that they did not notice the motion of visualizations because they were experienced and very used to the quick movement of game entities. They thought the movement of the visualization with their game characters was a natural property and in no way distracting: the visualization was embedded in the game and, as such, should move with its game character. Reading visualization under motion may be a task that can be learned and be done naturally within another primary task. The effectiveness of learning to read visualizations certainly requires further study. In addition, knowing the limits for when even well-trained viewers can no longer read visualizations in motion well can aid visualization design for real-word contexts.

Designing and evaluating visualizations in motion in real-world contexts: Our study results show that participants considered many trade-offs when ranking their visualization design preferences. Participants were not limited to a visualization's readability or aesthetics but also considered the design harmony with context and the support of their primary tasks. The dilemma of preference reveals that when designing visualizations in a concrete context with primary tasks, designers need to understand (motion) context, tasks, users, and how these factors are related. The functional role of a visualization may change drastically depending on the context. For example, in sports analytics, an embedded bar chart on the predicted shooting ratio can improve the audience's watching experience but will not detract from viewers' primary task — viewers can still watch the match without the visualization, and the result of the match will not be changed due to the lack of visualization. In contrast, in video games, if one does not read a health bar correctly the primary task will be impacted.

In the ranking of the `fully-integrated design` condition, a divergence of participants' priorities was particularly evident. Some participants preferred to see an innovative design even if they were not familiar with the novel representation, and as such accepted that their regular gaming performance might be reduced. In contrast, some participants who cared about task completion, preferred the typical design that they were most familiar with. As such, to improve the user experience and maintain the effectiveness of visualization, it might be important to let players set their preferred representation, even for the same data.

The trade-offs participants described in regards to their preferred visualizations point to an important challenge for evaluating future visualizations in motion in realistic contexts. Had we focused on only one particular measure (mission support, engagement, readability, aesthetics, or gaming experience), we would have only seen a small part of the bigger picture that affected how the visualizations were experienced under motion. It seems crucial that in any real-world context visualizations in motion will be evaluated under a variety of aspects that take into account contexts, tasks, and user preferences. We found it very useful to apply an interview methodology coupled with a qualitative analytis to receive more details about how participants traded off the different aspects of their experience.

Informing visualization research: Avenues for further study In the paragraphs above we already point to several open questions for future research on visualizations in motion in realistic contexts. Our findings from the systematic review about what visuals and data are shown, where in-game visualizations are embedded, on what referents, and why they move, can all open interesting avenues for future research for embedding visualizations in motion-prone real-world contexts. For example, we can consider studying text and symbol readability under motion (not just visualizations), and visualization readability when motion is or is not driven by the user, or when motion is present on different backgrounds. In addition, the results from the user study point to several open questions regarding how visualizations should be embedded in realistic contexts, how people will learn to read these visualizations, acceptable difficulty levels for readings visualizations in motion, and importantly whether guidelines can be extracted across contexts.

Video games as a context involves motion and contextual factors, as well as several parallel tasks (not just visualization reading). As such it presents an interesting test-bed to study visualization reading under motion, such as investigating how the readability of visualizations is affected under different types of movement or changing background conditions. Our study considered an FPS game, but racing games, for example, present other interesting dynamics, like extreme speed and angle changes or sudden lighting changes, under which to test visualization effectiveness.

6.6 . Summary

We set out to improve our understanding of visualizations in motion in a realistic context. We chose video games as our context, as several already include visualizations in motion, and because visualization reading is not the players' primary task. Our goal was not to provide recommendations about how to design visualizations for video games in general, not for a particular game type. Instead, our goal was to use video games as a testing platform to tease out design considerations when including visualizations in motion in a real-world context and to study how they can affect user experience overall. Our results highlighted the importance of testing visualizations in a real-world context under multiple inter-related aspects: We saw clear trade-offs between visualization readability, perceived aesthetics, immersive visualization design, and primary task support.

7 - FUTURE WORK AND CONCLUSION

With the development of computing technologies, visualizations have been moved off paper to interactive media and even physicalized. Viewers can interact with visualizations by zooming, panning, and rotating on digital devices or moving around a physicalization to have a 360° view. In these cases, the relationships between a visualization and its viewer can be characterized by relative movement. I proposed and defined *visualization in motion* as visual data representations used in contexts that exhibit relative motion between a viewer and an entire visualization (Chapter 1). I proposed *visualization in motion* as an umbrella under which the perception of visualizations under motion and the impact of relative movement on the experience with visualizations can be discussed and analyzed. I classified visualization in motion into three categories according to the relative movement relationships between visualizations and viewers: (a) a moving visualization & a stationary viewer, (b) a moving viewer & a stationary visualization, and (c) a moving visualization & a moving viewer (Table 1.2). I illustrated existing and promising application scenarios for each category (Chapter 2).

In this chapter, I first summarize my thesis work, my contributions to visualization in motion, and the broader visualization research area. I next discuss the lessons I learned, my reflections, and the limitations of my work. I also propose some perspectives toward future work on visualization in motion. I end this dissertation with a conclusion section.

7.1 . Summary and Contributions of My Thesis

In this section, I provide a short summary and describe the main contributions of my thesis. My contributions are highlighted in **bold**.

To understand research challenges as well as to seek research opportunities for *visualization in motion*, I proposed **a research agenda** (Chapter 3). I discussed how the motion characteristics, including moving speed, movement trajectory, acceleration, and moving direction, might affect the readability of visualizations in motion. I also discussed the spatial relationships between the visualization, the viewer, and the world space. For instance, how the change in viewing distance, viewing angle, and perspectives would affect the perception of visualization. Furthermore, I presented factors related to the situatedness that need to be considered when designing visualizations in motion. These factors include motion autonomy, predictability of motion, context, connections between visualization and its data referent, and general design parameters of visualizations. Last, I illustrated possible devices and techniques that can be used to generate visualizations in motion, such as stationary screens, mobile and wearable devices, physicalizations, AR/VR, and advanced techniques (*e.g.*, holographic projections, drones, and robots).

I started my exploration of this research agenda with a basic question: How do motion characteristics affect peoples' ability to read visualizations in motion? I conducted **a series of crowdsourcing perception studies** with 240 participants (Chapter 4). In my studies, I tested two motion characteristics: moving speeds and movement trajectories. I asked participants to estimate proportions shown on moving donut charts and bar charts as quickly as possible. My quantitative analysis showed that motion characteristics have an impact on the readability of visualizations in motion. Higher speeds and irregular trajectories generally lead to more errors. The good news is that people can still get reliable information from visualizations in motion, even at high speeds and under irregular trajectories. Participants' estimation was very close to the exact value that they had to read. Differences of reading accuracy between a visualization in motion and a stationary visualization were less than 3 percentage points. In both speed and trajectory experiments, participants performed slightly better on donut charts than on bar charts, but the differences between the two representations were not huge, again under 3 percentage points.

Based on my perception results, I moved toward a real application scenario and asked how to design and embed visualization in motion (Chapter 5). I selected swimming as my usage scenario. Swimming has rich, dynamic data, of which only a small proportion has been visualized. Also, people are more accurate in visualization in motion perception under linear trajectories, and swimming can provide such trajectories. To investigate the current visualized data, their representations, and their movement status in swimming, I first conducted **a systematic review** of Olympic swimming videos. Next, to investigate which data was interesting to see for the general public, I ran **an online survey** with 80 swimming enthusiasts. After which, to design visualizations specific to swimming data and its context, I organized **an ideation workshop** with 7 visualization practitioners. I asked participants to sketch visual representations on transparent sheets and put these sheets over images of swimming backgrounds. Participants could move the sheet to stimulate the movement of visualizations. However, such a low-fidelity design method was not efficient enough for a motion context, as the movement of swimmers, as well as the coupled motion effects between the situated visualizations and the context, were missing. To fill the gap of missing motion context and motion effects in the design process, I developed **an interactive technology probe** [2] that allows users to instantly embed visualizations, modify design parameters, determine the visualization's movement status, and preview motion rendering effects on live swimming videos. To evaluate how motion context completeness would affect the design process, I conducted **a design evaluation** with 8 designers. My qualitative analysis shows the importance of full access to the motion context and the impact of the motion effects on design decisions.

In a concrete context such as swimming, the audience's primary task is to watch the race rather than follow and read the embedded visualizations in motion. In such a case, reading visualizations in motion might be affected by the other in-context tasks, but the visualization may also distract people from other tasks. I, therefore, explored how context affects the visualization in motion design as well as its user experience (Chapter 6). I selected video games as a test platform because video games have (a) rich gaming data and in-game visualizations, (b) busy and varied backgrounds, and (c) a primary task (winning the game) to complete. To understand the representations, embedding locations, and data shown of existing visualizations in motion in video games, I, and my co-advised Master intern, Federica Bucchieri, first conducted a systematic review (Section III in the appendix). We selected 50 video games and collected 160 examples of in-game visualizations in motion. We found that the current visualizations in motion embedded in games encode rich types of data, have various representations, and have different embedding locations. We next developed a first-person shooter (FPS) game, RobotLife, that allowed us to embed and test different designs of visualization in motion. We selected health as our data type because of its high frequency of appearance in FPSs. We varied visual representations and embedding locations in our tested designs: a bar chart over the head of the game character (non-integrated design), a texture (a vertical bar) that is fully integrated into the skin of the character (fully-integrated design), and a donut chart overlapping with an eye of the character (partial-match design). To investigate the user experience of visualizations in motion in a real-world context with a primary task, I conducted **a user study** with 18 FPS players. My quantitative analysis shows a clear trade-off between the design's readability and aesthetic. The non-integrated design was found to be more readable but less aesthetic, while the fully-integrated was the opposite. My qualitative analysis showed that a lot of factors affect the participants' user experience, including the experience of immersion the visualization design brings, the primary mission support the design gives, and the harmony between the design and its context. Designers need to balance these factors depending on how crucial the visualization is to the primary task.

To summarize, I first learned that people can read visualization in motion. I next understood that the design of visualization in motion requires full motion context. I then investigated that the visualization in motion design in a concrete context can affect the user experience, and thus, the design of visualization in motion requires careful consideration of the context.

7.2 . Discussions on Visualization in Motion & Limitations

In this dissertation, I provide dedicated discussion sections per contribution in the associate chapters. Therefore, here, I discuss on *visualization in motion* and the limitations of my work.

Ubiquitous visualizations Vs. Limited techniques: I proposed *visualization in motion* as a new research direction. With the development of ubiquitous settings, such as the popularity of wearable and augmented reality devices, visualizations in motion will become more and more important in visions of the future. In which visualizations in motion are embedded everywhere in our environment. However, there are still lots of technical limitations. For example, which data needs to be presented in the public world, how to collect such data from the physical environment, and how to best design their visual representations and present them in the physical world are still challenges. As such, it is still important now to do research on *visualization in motion* to help shape this future.

Static Vs. Moving visualizations & perceptual limits: I classified *visualization in motion* into three categories: one involving stationary viewers and two involving moving viewers. When viewers are static, it is essential to explore how to design situated visualizations in motion and how they can affect the reading experience because it is not possible to avoid the relative movement between viewer and visualization. However, when the viewers themselves are also moving, we can envision approaches where visualizations can be set to move with them to achieve a relatively static position wrt to the viewers. Previous work in computer vision [84] developed tracking algorithms to lock an object and fix its coordinates related to its viewer. As such, the relative static relation between the viewers and the visualizations can be maintained. Also, my perception studies show that motion characteristics did have a negative impact on the readability of visualizations in motion. This raises the following question: Under which scenarios should the motion effects be avoided to reach a better perception of visualization?

Intersection between visualization in motion, animation, and interaction: I defined *visualization in motion* as relative motion that exists between an entire visualization and a viewer. According to my definition, there are some intersections between visualization in motion, animation, and interaction. Visualization in motion relates to the movement of the entire visualization, while the animation relates to the motion effects inside a visualization. For example, scrolling a map on a tablet can be considered as visualization in motion because the entire map is moving. Scrolling is an interaction to move the map, and the movement of the map is realized by animation. Similarly, zooming and panning a big visualization on a digital device also need interactions to move and animations to express motion effects. In such intersecting cases, interaction provides opportunities to create visualizations in motion, and animations can be the techniques to realize visualizations in motion. However, reading visualizations in motion may not be the most interesting aspect to study in these situations because the displacement of visualizations is done in a very short time and may not require continuous reading during the movement. Research opportunities existing in such cases might focus more on interaction and animation techniques, such as how to make transitions to achieve smooth visualization reading when interacting with visualizations.

Limitations during my doctoral study: I started my topic during the coronavirus epidemic. At that time, we were not allowed to conduct lab-based or in-person studies. Thus, I started my exploration with moving visualizations & stationary viewers that could fit into crowdsourced experiments. I continued my exploration under this category but also put an eye on other categories. I first proposed a research agenda with Islam *et al*. [201] for moving visualizations & moving viewers, with a specific focus on mobile and wearable devices. We discussed research challenges in scenarios that people need to read from their fitness trackers while exercising. I then did a 3-month research visit at the University of Calgary and started work on investigating how to design visualizations in motion for mobile and wearable devices when viewers are exercising. This project is still in progress when I hand in my thesis. Furthermore, I explored how the movement of viewers can affect the reading accuracy of moving visualizations. This work is collaborated with Grioui *et al*. and is under review. Nevertheless, I did not experiment with the category of moving viewers and static visualizations during my doctoral study. I hope to expand my focus on visualization in motion in the future.

7.3 . Future Work

In this section, I discuss some possible future research directions for visualization in motion.

7.3.1 . Investigating Further Perception of Visualization in Motion

In my thesis, I investigated how moving speeds and movement trajectories affect the readability of visualizations in motion. Nevertheless, speed and trajectory are only a few of the factors that might affect the perception of visualization in motion. Other factors such as acceleration — how fast the speeds change, direction — where the visualization will go, and background pattern changes due to the movement might also have an impact on the reading accuracy of visualizations in motion. Also, my studies were conducted in a 2D space. It is still unknown how the readability of visualizations in motion might be influenced in a 3D space. For example, different perspectives can bring different viewing angles and viewing distances, which could lead to different perceived sizes and shapes of visualization on viewers' retinas. Furthermore, the combination of factors, such as a varying speed in a 3D space (which is closer to what we have in a natural context), is still an area worth exploring more. Further studies are required to build a complete perceptual foundation of *visualization in motion*.

7.3.2 . Developing New Visualization Techniques for Motion Context

I explored how to embed and design visualization in motion in a real application scenario — swimming. To reduce the latency and to provide a smooth viewing experience, I prepared in advance the swimmers' trajectory data that the visualizations moved along by computer vision algorithms. If new techniques can be proposed to facilitate the combination of object detection/tracking and visualization rendering, instant use of tracked trajectories for visualizations in motion can bee achieved. As such, making extensive embeddings of visualization in motion into live scenes can become a reality. We can thus envision new visualization authoring workflows, for example, a visualization library or toolkit that can be directly called to draw visualizations during the object detection/tracking process.

7.3.3 . Proposing Context-awareness Design Guidelines

My work showed that the context can affect the user experience of visualization in motion. Yet, there are few design guidelines for visualization that specifically focus on contexts with motion factors involved. In different contexts, visualization in motion plays various roles. For example, in sports analytics, visualizations in motion are embedded to let audiences understand the race and gain more insights. The visualizations in motion are not protagonists, as the race result is not affected by the absence of the visualizations. As such, the design of visualization in motion should not dominate the viewing experience in such contexts. In contrast, visualizations in motion play a more central role in other contexts — the design of visualization can directly affect the mission results. For instance, in video games, in-game visualizations in motion are embedded to help players make quick decisions to win the game. A lack of visualizations or a badly designed visual representations might lead to failure. How to best design, embed, and display in-context visualization in motion (*e.g.*, embedding locations, entering & fading techniques, binding between visualizations and their referents) remains an open question. As such, further empirical studies are required to propose dedicated design guidelines for *visualization in motion* with associated contexts.

7.3.4 . Building A Design Space of Visualization in Motion

I started my thesis with moving visualizations & stationary viewers and continued my work under this category. However, the other two categories, moving viewers & stationary visualization and moving visualization & moving viewer, also involve relative movement relationships between visualizations and viewers and bring different research opportunities. For instance, when viewers are moving while visualizations are stationary, how to minimize the impact of viewing angle and viewing distance changes on viewing scope, how to match the visualization to different perspectives, and how to overcome the deforming of visualizations under motion are still challenges. On the other hand, when both viewers and visualizations are in motion, such as doing exercises with wearable devices, how to best design in-context visualizations to be seen on limited-size screens and how to inform viewers of their live fitness data when the vision channel is partially or not available (*e.g.*, a swimmer who is swimming cannot read from their smartwatch unless they stop) also need further exploration. I reflected on such scenarios in my collaboration with Islam *et al*. [201]. We proposed a research agenda on *visualization in motion* involving wearable devices. Furthermore, I contributed to a first empirical results on reading visualizations on-the-go with Grioui *et al*. (this work is under review). Nevertheless, we are still far from a final design space of visualization in motion combining perception results, visualization techniques, and design guidelines.

7.4 . Reflections & Lessons Learned about Research

In this section, I discuss my reflections and lessons learned about research.

Fair remuneration for participants with specific skills: In my design evaluation of the technology probe (Chapter 5), I recruited and collaborated with professional and senior designers. Designers spent their working time and put much effort into my study. However, following the payment policy of my institution, I could not pay the designers according to their salary on the market, but only a box of chocolate whose value barely equals the legal minimum wage. I lost one promising designer with more than 20 years of experience because our remuneration could not match their work and the valuable comments they would bring. The payment dilemma not only exists when collaborating with designers but also with other domain experts. Compared to their salary on the market, remuneration that only meets the law requirements might bring additional difficulties to research and can lead to low-quality output.

Co-building video library with open-access copyright: My thesis is deeply related to motion. As such, video material is important for a significant part of my work, such as sports videos (Chapter 5) and video recordings of games (Chapter 6). However, unlike rich open-access figure libraries, high-quality video libraries without copyright conflicts are rare. One of my collaborators recorded our videos under the authorization of the French National Swimming Federation [36] and combined and processed the videos afterward to obtain a usable one. Nevertheless, our processed video was not of the same quality as the ones broadcast on TV. The camera perspectives we could get were limited. Similar copyright issues also exist in broader research domains that need to embed visual data representations in videos, such as sports analytics, augmented reality, and computer vision. I released our video under the Creative Commons CC BY-SA license 🅭🅯🄎 and uploaded it on OSF [235], which is an open science platform. A better future for work on visualization in motion would involve the visualization community to co-build an open video library containing freely usable data without copyright barriers.

Putting effort into writing: I graduated from an engineering school. I received almost zero writing training before my doctoral study. In my engineering training, getting things done was more important than a good expression. Thus, at the beginning of my thesis, I spent most of my time making things and minimal time writing. Such a pitfall directly led to my messy manuscripts. Some conferences rejected my manuscripts because I could not write down my contributions as clearly as what I had in mind. I had to spend extra time on the revision and resubmission.

I realized that writing is as essential as making projects. Telling a good story can help readers better understand my work. I continue to learn to write, but it is a long process that takes time and effort.

Sufficient discussion and testing on study design: In my first crowdsourcing experiment (Chapter 4), I spent extra time re-implementing the whole study due to the inadequate discussion. I always remembered this lesson in my following study designs. I also reminded other doctoral students about their study structure. One junior fellow was grateful for the suggestion that I gave.

7.5 . Conclusion

In my thesis, I defined *visualization in motion* and classified *visualizations in motion* into 3 categories according to the movement status of viewers and visualizations. I provided initial fundamental empirical results that showed that people can read visualizations in motion. Furthermore, I explored how to design *visualization in motion* and built an interactive technology probe to embed visualizations in motion in a real application scenario. Last but not least, I investigated the impact of context on the design of *visualization in motion* as well as its user experience. My work shows the impact of motion characteristics on visualization perception, the significance of the motion context in the design process of *visualization in motion*, and the influence of the real-world context on *visualization in motion* design and its user experience.

Appendix

I . Movement Trajectories Used in Perception Studies

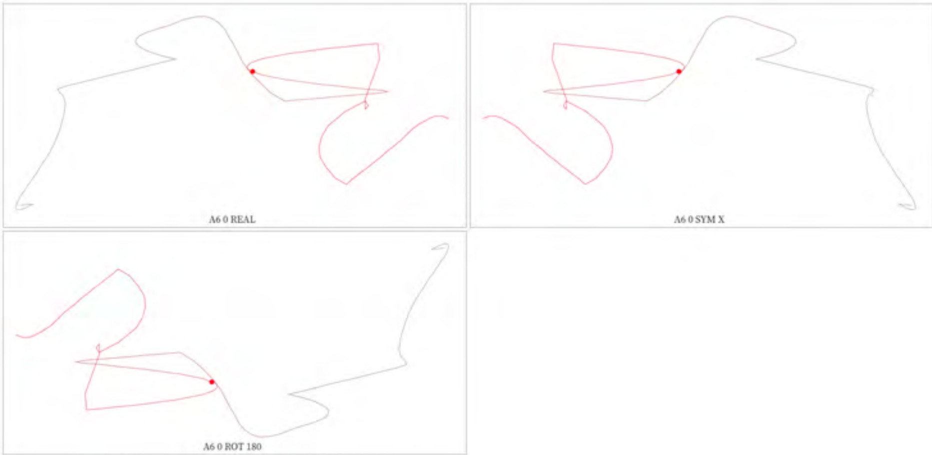


Figure 1: Real trajectory and its $180°$ clockwise rotation and a mirror on the y axis used in Trajectory Experiment - `Slow` × `Irregular`.

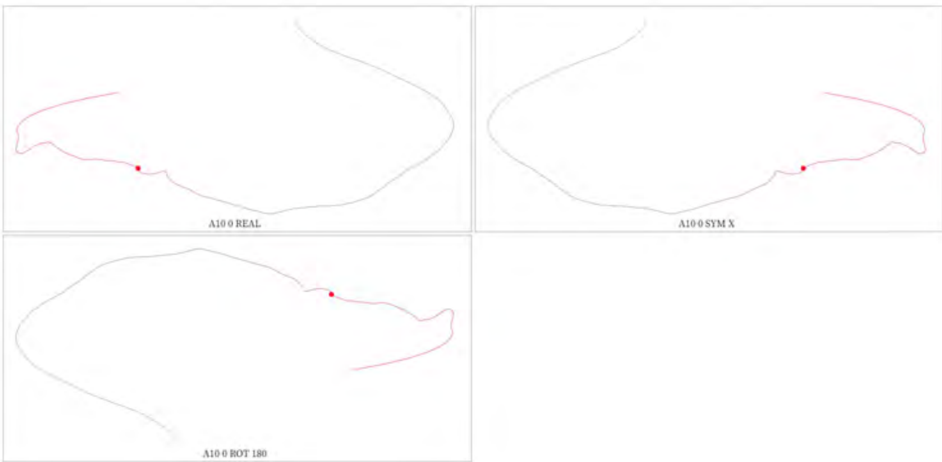


Figure 2: Real trajectory and its $180°$ clockwise rotation and a mirror on the y axis used in Trajectory Experiment - `Slow` × `Irregular`.

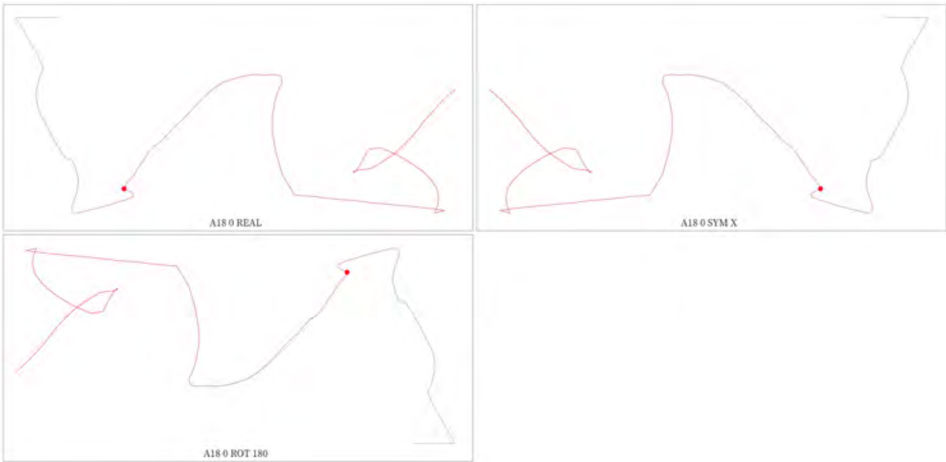


Figure 3: Real trajectory and its $180°$ clockwise rotation and a mirror on the y axis used in Trajectory Experiment - `Slow` × `Irregular`.

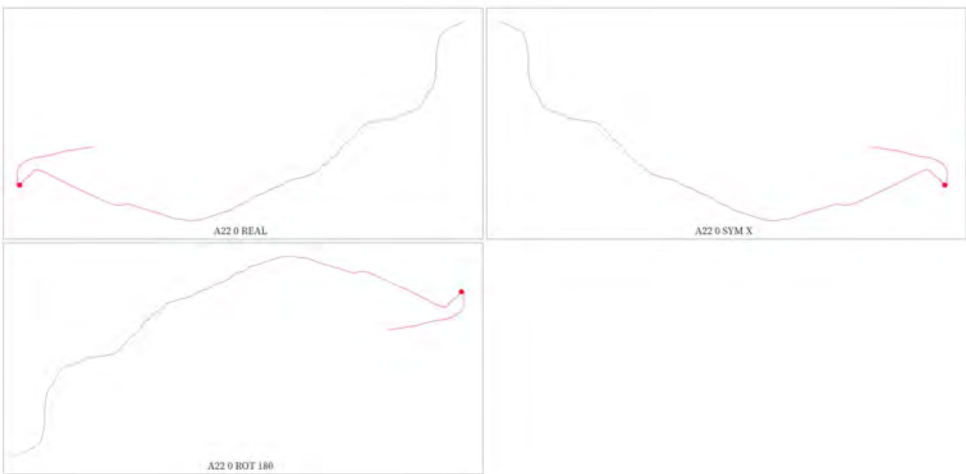


Figure 4: Real trajectory and its $180°$ clockwise rotation and a mirror on the y axis used in Trajectory Experiment - `Slow` × `Irregular`.

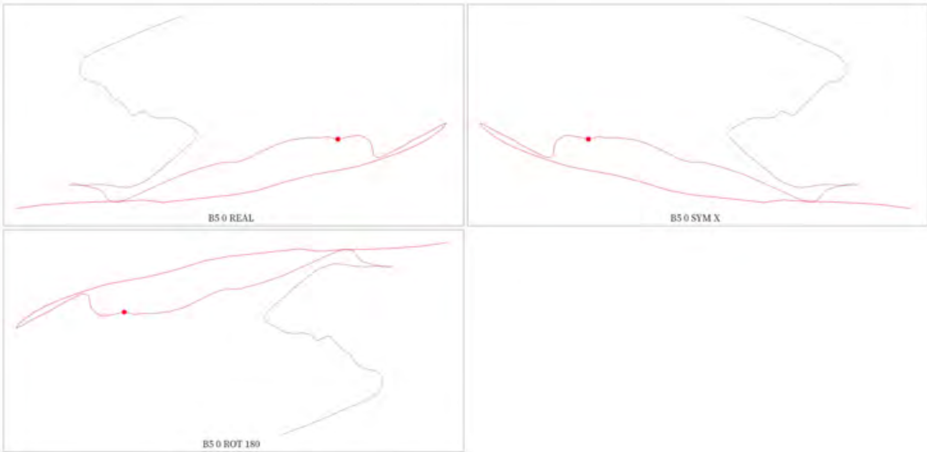


Figure 5: Real trajectory and its $180°$ clockwise rotation and a mirror on the y axis used in Trajectory Experiment - `Slow` ⪢ × `Irregular`.

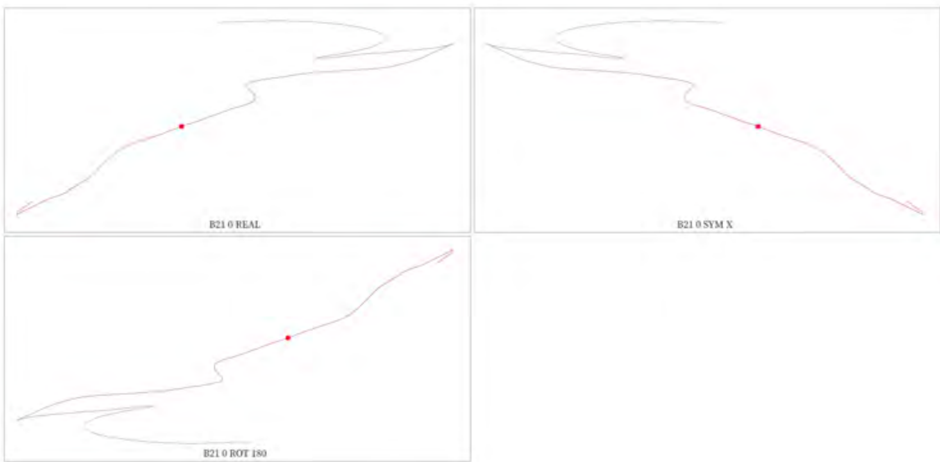


Figure 6: Real trajectory and its $180°$ clockwise rotation and a mirror on the y axis used in Trajectory Experiment - `Slow` ⪢ × `Irregular`.

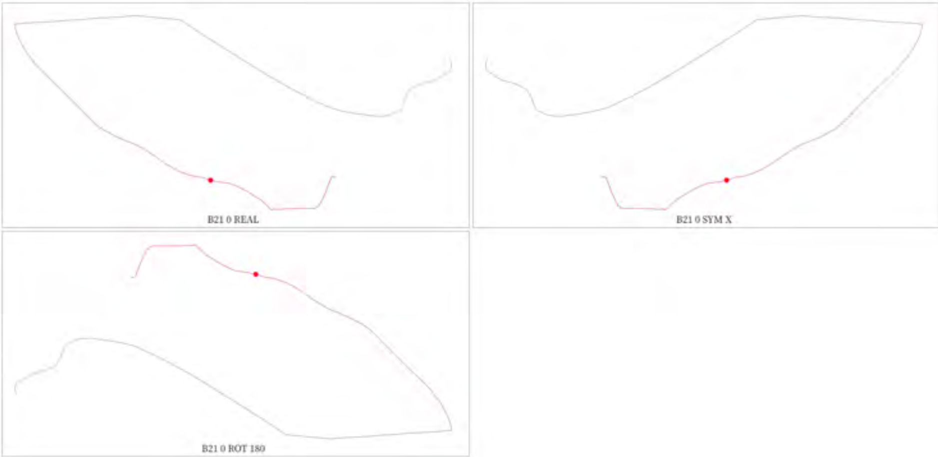


Figure 7: Real trajectory and its $180°$ clockwise rotation and a mirror on the y axis used in Trajectory Experiment - `Slow` × `Irregular`.

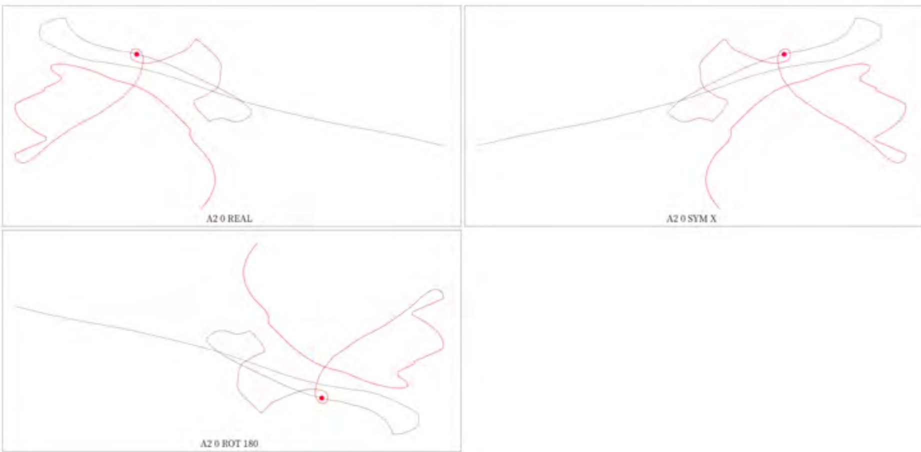


Figure 8: Real trajectory and its $180°$ clockwise rotation and a mirror on the y axis used in Trajectory Experiment - `Fast` × `Irregular`.

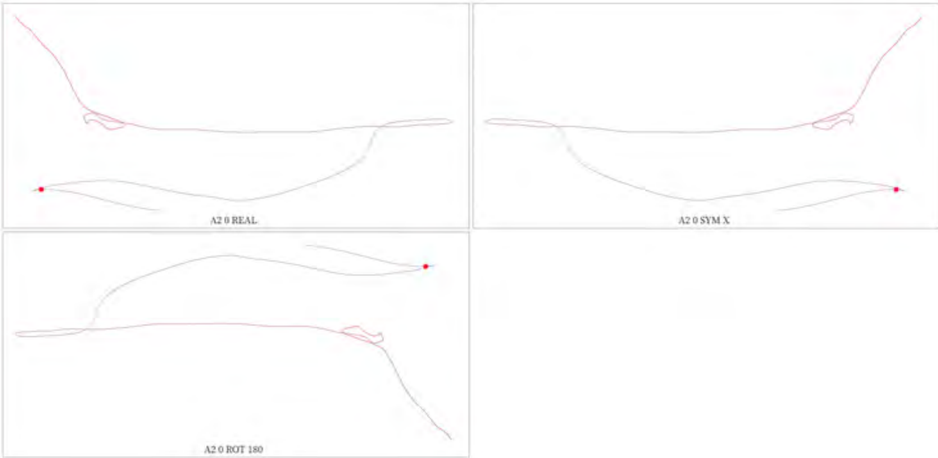


Figure 9: Real trajectory and its 180° clockwise rotation and a mirror on the y axis used in Trajectory Experiment - `Fast` × `Irregular`.

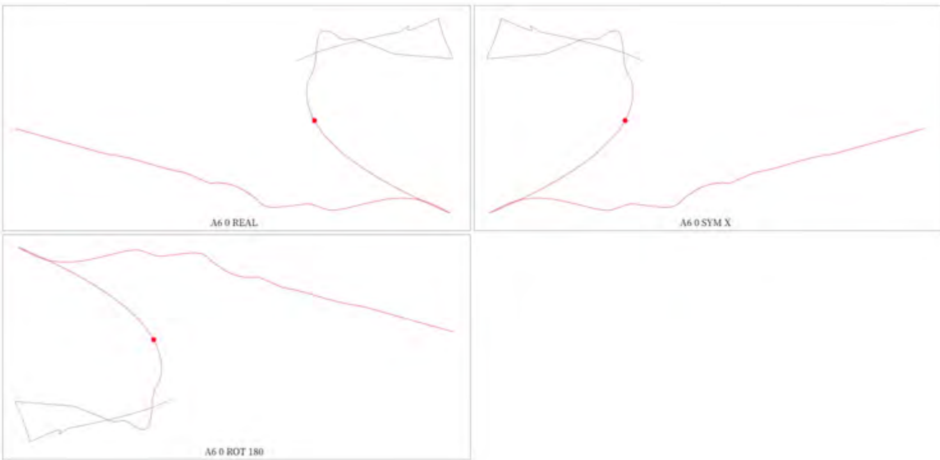


Figure 10: Real trajectory and its 180° clockwise rotation and a mirror on the y axis used in Trajectory Experiment - `Fast` × `Irregular`.

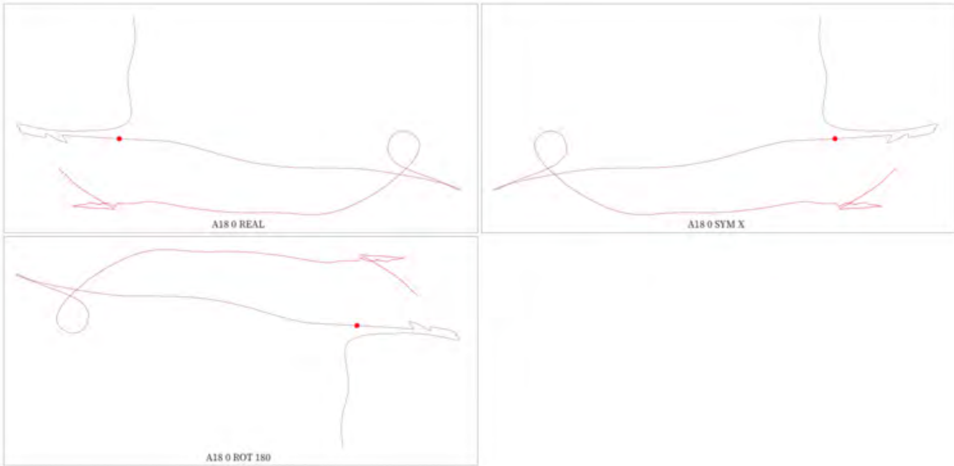


Figure 11: Real trajectory and its 180° clockwise rotation and a mirror on the y axis used in Trajectory Experiment - `Fast` × `Irregular`.

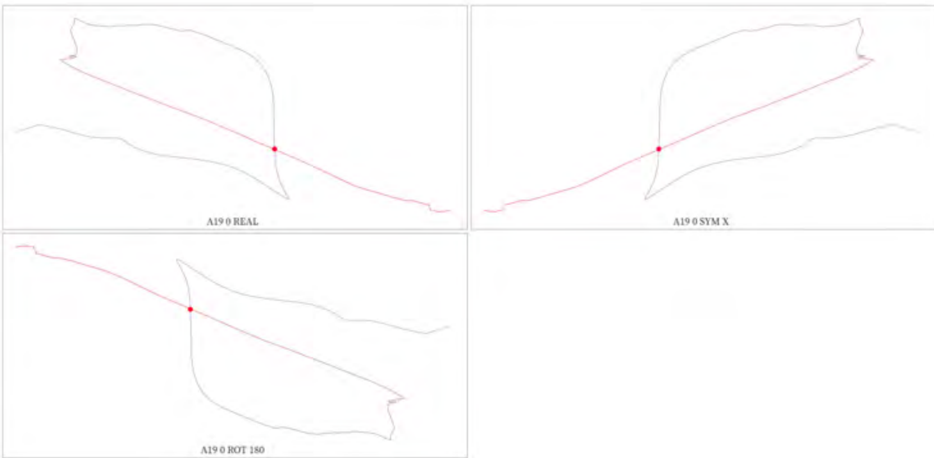


Figure 12: Real trajectory and its 180° clockwise rotation and a mirror on the y axis used in Trajectory Experiment - `Fast` × `Irregular`.

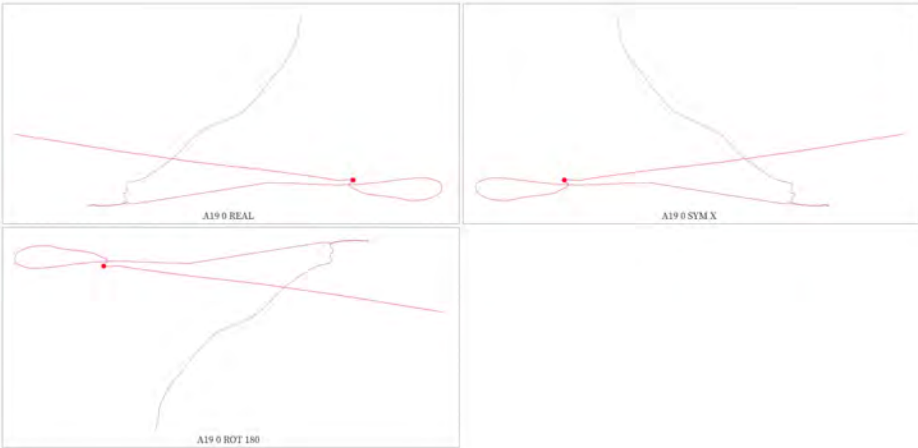


Figure 13: Real trajectory and its 180° clockwise rotation and a mirror on the y axis used in Trajectory Experiment - `Fast` × `Irregular`.

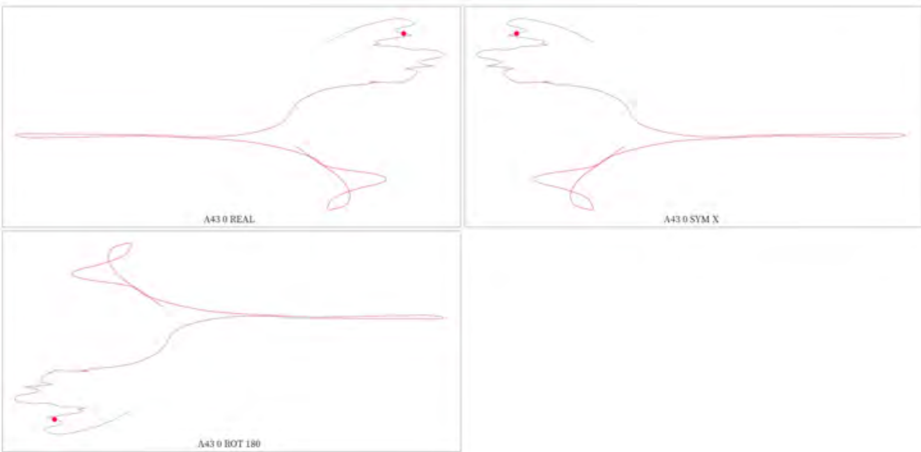


Figure 14: Real trajectory and its 180° clockwise rotation and a mirror on the y axis used in Trajectory Experiment - `Fast` × `Irregular`.

II . Supplemental Data Interests in Swimming Survey

the winner record for every match in history	Extremely interested
The strokes used in each stage of the medley	Extremely interested
How much strength is applied at the start on the block	Extremely interested
Distances to winner and to consecutive swimmers after completion of race (i.e. 5cm 2nd to 1st)	Extremely interested
Average number of stroke	Extremely interested
An alert whenever an underdog makes it to a race would make me more interested in that race	Extremely interested
Number of medals already won during the same event	Extremely interested
Cadence (strokes wrt time)	Extremely interested
Swimming styles (Breaststroke/Backstroke/Butterfly stroke/Freestyle swimming)	Extremely interested
Predict 1st, 2nd and 3rd from the start of last lap	Extremely interested
Takeover reaction time for relays	Extremely interested
In many auto racing events, while you are watching on TV, there is a companion web site that shows lap times. Would be great if some of the parameters like stroke frequency, distance per stroke would be posted as the race progresses.	Extremely interested
Underwater or emersion distances during start and turns	Extremely interested
Distance underwater (meters spent underwater off start and turns)	Extremely interested
AR data visualizations using the deep camera	Extremely interested
Comparison of number of stroke between swimmers	Extremely interested
It would be interesting to get a summary of who outperformed and who failed to meet expectations	Extremely interested
Number of gold medals at the Olympics	Extremely interested
The race data collected by your technology is posted on a web site for fans to view after the event is over. The sport of swimming really does not have the “stats” element that other sports have had for decades.	Extremely interested
Moments of breading	Extremely interested
Time and speed spent turning	Extremely interested
Number of silver medals at the Olympics	Extremely interested
At start and each turn: underwater distance and number of dolphin kicks	Extremely interested
Kicking Moments accelerations	Extremely interested
Distance under water when turning	Extremely interested
bronzesilver medals at the Olympics	Extremely interested
Distance of entering the water at the start	Extremely interested
When they emerged from the water compared to others	Extremely interested
QR code or link to a web page presenting the swimmer	Extremely interested
Distance inside the water (braces)	Extremely interested
False start	Extremely interested
Disqualification	Extremely interested
Reaction time of all swimmers during relays	Extremely interested

Figure 15: Other interesting data optional supplemented by participants - Part 1.

heart beat	Very interested
Improvement compared to PB	Very interested
Stroke tempo (duration to complete a stroke)	Very interested
AR visualizations when the hand is touching the wall or the clock	Very interested
Swimming Club and Trainer	Very interested
Curve evolution performance per athlete	Very interested
Flip turn timing	Very interested
Données sur l'entraîneur	Very interested
Probablility of winning	Very interested
diving distance (after starts and turns)	Very interested
Time they took for the turn at the wall when they arrive to when their feet leave the wall	Very interested
heartbeat	Very interested
comparison with previous races of the same swimmer	Very interested
Relevant doping history	Very interested
The distance at which swimmers enter the water with their dives	Very interested
Training kilometers or training techniques before a race starts	Very interested
Sporting successes (e.g. European Champion)	Very interested
Age	Very interested
Distance at peak swimming speed (25m or 50m)	Very interested
Données sur les conditions et lieux d'entraînement	Very interested
Swimwear(high technology)	Very interested
velocity underwater	Very interested
current year ranking (7th fastest swimmer this year)	Very interested
number of underwater kicking cycles during start and turns	Very interested
Number of underwater kicks (off to start and turns)	Very interested
Timing of the different swimming phases (reaction time, flight phase, diving time, swimming time, flip turn time)	Very interested
Situer les participations à différentes compétions et leurs résultats	Very interested
Probability of record breaking	Very interested
all time ranking (7th fastest swimmer of all times)	Very interested
Number breath and which side per 50m	Very interested
Speed after turn (how good the turn is)	Very interested
Infos on successes or PBs of swimmers just before the race	Very interested
Development of swimming times of a swimmer (before race starts)	Very interested
Personnel record sum of remaining swimmers in relay	Moderately interested
Recent évolution of personal record (within a year)	Moderately interested
Swimmer's previous olympic awards	Moderately interested
Speed data analysis of athletes in event	Moderately interested
Swimmer's energy depense estimation	Moderately interested
How far they jump from the blocks	Moderately interested
How fast a swimmer turns	Moderately interested
Connaître le décalage horaire dans lequel se situe le nageur	Moderately interested
power deployed by the swimmer (Watts) - for long races	Moderately interested
Water position of a swimmer	Moderately interested
The athlete's highest performance in this event	Slightly interetsed
breath	Slightly interetsed
Strokes per lap	Slightly interetsed

Figure 16: Other interesting data optional supplemented by participants - Part 2.

III . A Systematic Review of Visualization in Motion in Video Games

Visualizations in motion are prevalent in video games. As such, their design needs to be adapted to fit the motion context while allowing people to focus on the game and get helpful contextual information at the same time. We consider existing visualizations in motion in video games as artifacts that can be studied to understand decisions designers made to adapt data representations to this context.

To understand how designers dealt with the various challenges related to motion in video games, we reviewed visualizations from 50 games and 17 different genres. In total, we found 160 examples of visualizations in motion that we categorize according to different dimensions. In the development of our categories we were inspired by the work of Islam *et al*. [3] in their analysis of existing visualizations in use on watch faces. The dimension used by Islam *et al*. described the visual design of data representations and the data used which we also included. We extended their categorization by adding dedicated dimensions related to motion factors and video games. To further understand how different data are shown, we also classify the representations designers chose for different data types. Next, we describe the video games selection, the categorization of the visualizations found, and the results that emerged from our systematic review.

∗ . Selection of Video Games

To cover a diverse selection of video games we used a commercial ranking website called Metacritic [236]. Metacritic assigns a unique Metascore to each video game and categorizes games according to 18 different game genres. For each genre we selected the top 3 games from 2011–2022 across all gaming platforms. We excluded puzzle games, because on a first inspection they did not contain moving visualizations. Moreover, for the wrestling genre we found and selected only two games that contained relevant visualizations. We excluded games without a Metascore and maintained one of the games from the same series (*e.g.*, *Super Mario Galaxy* [237] and *Super Mario Galaxy 2* [238]). In total, we reviewed 50 games from 17 genres. For each game, we watched game-plays on YouTube for approximately 5 to 15 minutes and video-recorded relevant parts of the videos where the game showed visualizations in motion.

† . Categorization of Current Video Game Visualizations

We collected 160 examples of visualization in motion. The genres with most occurrences were Role-playing Games (RPG) with 18/160 visualizations, strategy games with 16/160, and wargames with 14/160 samples (Fig. 17). We categorized these visualizations according to multiple dimensions related to situated visualization and motion characteristics:

Visual representation: describes how data was represented. Signs (*e.g.*, icons, arrows) and bar charts–both linear and circular–were the most prevalent representa-

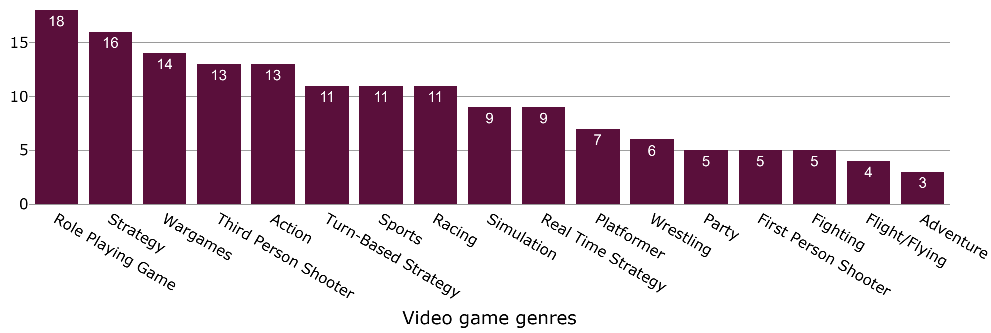


Figure 17: Number of visualizations in motion per video game genre.

tions (36/160), followed by labels with numbers (21/160) and labels with texts (19/160). Table 1 summarizes all the representations found.

Data referents: are the entities the data refers to. We found three types of referents: characters, locations, and objects. A character is an actor in the game controlled by a player or an AI together with its own visible equipment like guns, armours or clothes. A location is an area or point of interest inside the scope of the game (*e.g.*, objective's position, area of attack, checkpoints). An object is any nonliving entity that the player can interact with. Most 114/160 data referents were characters, followed by 30/160 locations, and 16/160 objects.

Data dimensions: refer to the data represented in each visualization. Visualizations showing only a single dimension were the most common case (128/160), while 31/160 samples encoded two dimensions and only one encoded three types of information. Often, additional dimensions were derived from a primary dimension. For example, in addition to showing a character's health percentage, various games applied a color encoding to represent a health status. A widely used encoding used a traffic light color scheme with green, yellow, and red for healthy, medium, and critical health levels.

Color appearance: refers to how the visualizations' colors were integrated. We

Table 1: 160 Visualizations in motion found in the 50 analyzed video games.

Representation	Count	Representation	Count
Signs	36	World annotation	5
Bar chart	36	Circle	4
Label with numbers	21	Map	4
Label with text	19	Pictograph	4
Areas	10	Ludophasmas	3
Color overlapped	8	Heatmap	2
Silhouettes	6	Pie chart	2

(a) Stamina bars and names embedded below the feet of the players in *NBA 2K21* [239].

(b) Heatmap overlapping the game environment in *Civilization VI* [240].

(c) Health counter integrated with the character's suite design in *Nintendo Land* [241].

Figure 18: Examples of visualizations in motion embedded in different locations with respect to the data referents.

divided color appearance into three groups: blended, salient or thematic. Blended colors make the visualization blend into the game context. The visualization does not stand out through its design. Potentially, this makes the visualization easily ignored or difficult to read but may create a more immersive experience. Instead, salient colors makes the visualization highly visible; either through the use of untypical hues or through a very high contrast with the game context. Finally, thematic combinations use canonical colors for the data they represent or the color combination matches the video game's palette. The color appearances of 104/160 samples were thematic, while 41/160 were salient, and only 15/160 were blended.

Background consistency: considers if the visualization has a static or fixed background when a visualization changes its in-game position. When enemies move from one location in the game to another the visualizations attached to them may be displayed on changing backgrounds. If the background of a visualization is fixed, for example providing an opaque container behind it, there is a higher possibility that the visualization is always visible regardless of motion factors. Results show that 133/160 visualization's backgrounds were varying with the visualization position, while only 27/160 had a fixed background.

Embedding locations: indicate the spatial relationship of the visualization and the data referent. We found three different embedding locations. 121/160 visualizations were embedded *around the data referent*; for example above an object (Fig. 18a)), under the feet of a character, or above a checkpoint (a location). 26/160 visualizations showed full or partial *overlap with the data referent* as shown in Fig. 18b. Finally, 13/160 visualizations were *integrated with the data referent* permanently for example in the material color of the referent, in its design or in the diegetic elements attached to it (Fig. 18c). Although visualizations integrated or overlapped with the referent might look similar, integrated visualizations cannot be separated from the referent while overlays may be temporary.

Movement autonomy: considers if the visualization was moving autonomously or whether movement was caused by a player. For example, in Third-person shooter (TPS), the player controls a main character defined as the protagonist. By moving the protagonist, rotating its view, and changing the camera perspective, the player can induce motion of elements on the screen. Autonomous movement, instead, does not depend on the player's control for example when the camera is still and some characters are moving on screen. Autonomous movement was not prevalent in video games, only five visualizations moved autonomously, while 86/160 were consistently controlled in some way by the player and 69/160 depended on both autonomous movement and the player's control.

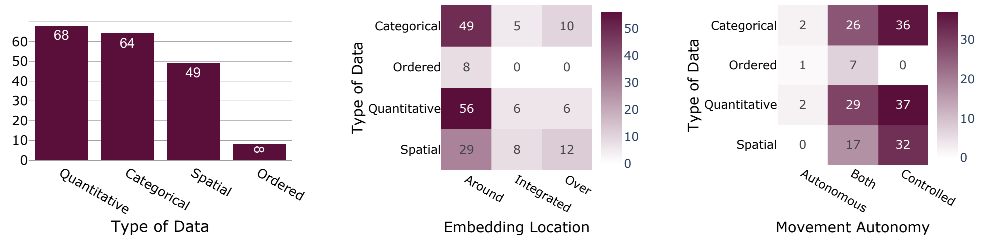
Visibility conditions: This dimension considers if the visualization is only visible when the player initiates visibility by focusing on the data referent. For example with hover, by pushing a button, using a special power and more. In this case we consider those visualizations to be *on focus*. If they are visible independently of the player's actions, they are *not on focus*. This mechanism is very common in FPS games where enemy health bars are only visible while the cross hair of the protagonist hovers the body of the enemies' themselves. The slight majority of the cases were not On Focus visualization (92/160), while 68/160 visualizations were On Focus.

Frequency of appearance: evaluates how frequently a visualization in motion appears during a normal gaming session. Since frequency is a relative measure, we categorized samples in four categories: Rare (11/160) were visualizations that appeared in exceptional cases (*e.g.*, progress bars of special actions); Moderate (13/160), defined visualizations that appeared from time to time (*e.g.*, secondary tasks related visualizations such as troops movement in resource management games); Frequent (118/160), appeared often but not continuously (*e.g.*, primary task related visualizations such health bars on focus for FPS games); Always Visible (18/160) were those visualizations that were always displayed on screen (*e.g.*, health of the main character in TPS game).

Foreground: indicates if the visualization is always in the foreground and cannot be overlapped. Occlusion is an important factor to consider in video games. If we imagine a scene with 20 enemies in front of the game protagonist, each one of them with a visualization displayed under their feet, it is likely that some of the visualizations will be poorly visible or totally hidden due to the occlusion caused by other elements. For example, a tree can hide some visualizations displayed near by. Being always in the foreground can help the visualizations to stand out and be visible. 110/160 visualizations were always in the foreground, while in 50/160 visualization could be overlapped by other game elements.

‡ . Representations by Data Type

The four most prevalent data types we found in our review were: quantitative, categorical, ordered, and spatial data. Analyzing the spatial relationship of the visualization and the data referent, there were some tendencies in the way different



(a) Number of occurrences of visualizations of different types of data.

(b) Number of occurrences of visualizations of different data types according to their embedding location.

(c) Number of occurrences of visualizations displaying different types of data showing different movement conditions.

Figure 19: Results of the analysis of different types of data visualized under motion in video games.

types of data were *embedded* in the data referent (Fig. 19b). The vast majority of each data type was embedded *around* the data referent, with one exception highlighted below. Regarding the *movement autonomy* of different types of data representations, most visualizations were in motion due to the player's control (Fig. 19c). Details per data type we analyzed:

Quantitative data: 67/160 visualizations represented quantitaties (see Fig. 19a). For example, as health points of a character, its stamina, or the number of resources crafted. Quantitative data was mainly represented by linear bar charts (28/67), labels with numbers (14/67), or circular bar charts (7/67) (Fig. 20). Quantitative data was very popular in strategy games, RPGs, and war games.

Categorical data: was the second most common, with 64/160 samples. Categorical data concerned team identification and resource type. It was represented as labels with text (18/64), signs (17/64), or by color-overlap on the data referent (7/64). Categorical data was frequently embedded in action, racing,

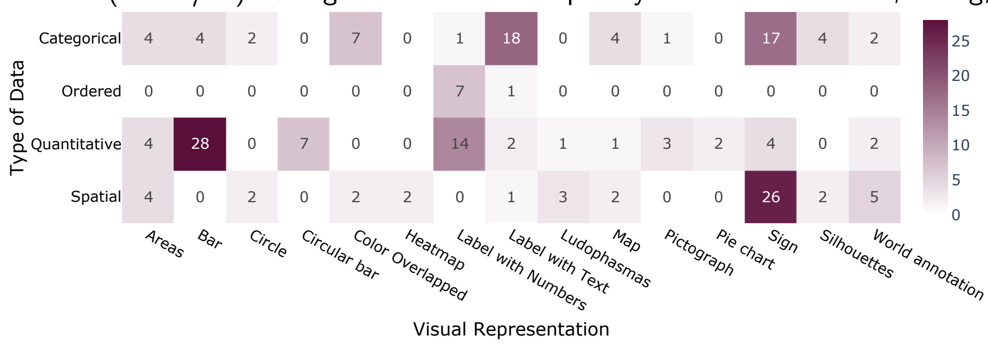


Figure 20: Number of occurrences of visualizations with various visual representation according to different types of data.

Figure 21: The RobotLife UI. The player's health and ammunition county are shown at the bottom in red and white bar charts respectively. Primary and secondary objectives of the game are displayed on the left of the screen, together with a pause button.

sport, and war games.

Spatial data: refers to position-related information, represented in 49/160 visualizations. Position was most commonly indicated by signs (26/49). This data was very common for mission objectives or interactive item positions. Also, the use of world annotations was common for spatial data (5/49). 29/49 visualizations were embedded *around* the data referent, 12/49 *overlapped* the referent, and 8/49 were *integrated* in the referent's design. Spatial data was often used in TPS games, action games and RPGs.

Ordered data: was the least frequent with 8/160 representatives. It was used in specific game genres like racing, simulation, and TPS games. (*e.g.*, for position on a leader board). Ordered data was represented with labels using numbers (7/8) or text (1/8) and that *only* around the data referent. It was also the only type of data that showed a majority of samples with a movement autonomy depending on both controlled motion and autonomous motion (7/8).

§ . Summary

We set out to understand how designers have in the past dealt with the challenge of designing visualization for a real-world context that involves motion, by reviewing the produced artefacts themselves. We found that designers predominantly produced small visualizations embedded around game characters. These small visualizations often showed only a single data dimension such as health, potentially with an added encoding of a derived value such as indicating how critical a health value may be. Designers used well-known representations such as signs (icons or arrows), length-encodings (round, horizontal, or vertical bar charts), or text. Designers used different strategies for how to integrate the visualizations in the context: while designs were not often integrated directly into the referent design or overlayed with it, they were placed around them (*e.g.*, around a character), and the visualization background often did adjust to changes in the scene, and finally the visualizations used color palettes that fit the theme of the game or were canonical colors. As such, visualizations were not blended deeply into the game world but were also not made to stand out excessively. We found this latter finding particularly intriguing, as a deeper embedding could potentially influence how immersed viewers feel, or how they otherwise experience the game and the visualizations moving within it. We, therefore, decided to more deeply explore this question of visualization embedding and its relationship to user experience in the game context when the visualization is in motion.

IV . RobotLife: A Video Game for Evaluating Visualizations in Motion

In a next phase of our research we set out to explore more deeply how choices around embedding location and visualization in motion design may affect user experience in the game context. To do so, we needed access to an environment that would allow us to collect game data, control the look-and-feel of the visualization, characterize their movement. Specifically, we wanted to ensure that relative motion factors of adequate magnitude were present between a seated player and the visualizations displayed on the screen, both dependently and independently of player control. We therefore developed our own video game, RobotLife — a FPS game set inside a robot factory. The game UI can be seen in Fig. 21. Based on the video game genres analyzed during the systematic review, we chose FPS as a motion-prone game genre. Looking at Fig. 17 the decision to chose FPS instead of other genres that produced more examples of visualization in motion may seem inconsistent. However, a single video game can fall under different categories, and many games in other Metacritic categories have close relationships to FPSs. In addition, FPS games are popular [226]. As such, we were confident that we could find experienced players for our user study.

∗ . Implementation

We implemented RobotLife using Unity, a cross-platform game engine [242] and by extending the *FPS Microgame Template* [243]. The FPS Microgame Template is a 3D First Person Shooter game available for free on the Unity Learn platform and can be modified and customized by developers. The microgame comprises level-building assets, weapons, props, enemies, and more. The microgame comes with the basic game mechanics already implemented: a first-person character controller provides an input recognition mechanism, a rudimentary environment is proposed in the sample scene, as well as the shooting mechanics to fight the enemies in the scenario. The microgame also proposed designs and implementation for hover bots, the flying robots inside the factory (Table 1.1).

FPS games are often centered around killing all the enemies without distinction. Players do not need to read the exact value of an enemy's health representation as their final goal is always to bring the health value to 0. For this reason, the mechanics of our game RobotLife were developed in a different way, forcing the players actually to read the health level and not blindly shoot at every enemy in the scenario.

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