January 2021

# Smart Glasses: The Road to AR's Holy Grail

An ARtillery Intelligence Briefing



ARtillery Intelligence

# Executive Summary

Augmented reality's traction over the past few years has occurred mostly through the smartphone camera. As we quantified in our recent mobile AR revenue forecast,[i] this early AR modality has reached scale by piggy-backing on a ubiquitous device we all carry.

But that scale has a tradeoff. Mobile AR's quantitative benefits come with qualitative detriments. In other words, though AR benefits from mobile's sheer reach, smartphones aren't the technology's optimal vessel. There, AR is overshadowed by other established and primary smartphone activities.

Beyond taking a back seat to other mobile use cases, AR's use on smartphones can be awkward and un-ergonomic. Arm fatigue sets in through the act of holding one's phone up for long periods to experience line-of-sight graphical overlays. This keeps session lengths short.

Put another way, AR is a bolted-on technology for the smartphone, rather than a native one. A device that has an inherently downward-held orientation wasn't made for a technology that integrates graphics with line-of-sight perspectives. The result: AR's smartphone activations are relatively unnatural.

"Relatively" is the key word, as mobile AR has seen some success, such as **Snapchat** lenses. But to achieve "native" orientation, AR's true home awaits in glasses form. AR's potential and its consumer appeal won't be fully unlocked until it can realistically be housed in *wearable* eyeglasses.

But that's easier said than done. The underlying technology isn't yet at the stage where graphically-robust experiences can be integrated with glasses that most average consumers will wear. Conversely, stylistically-viable smart glasses can't have the graphical intensity for a worthwhile user experience.

This is a design tradeoff that AR glasses hopefuls continue to grapple with. At one end of the spectrum are AR headsets like **Microsoft** HoloLens 2 and **Magic Leap** One – graphically compelling but stylistically untenable. At the other end is hardware such as **North** Focals – sleek but underwhelming in graphical intensity.

Until the day when these factors can co-exist, tradeoffs will continue to be made, where individual use cases (think enterprise versus consumer) determine the optimal target along that sliding scale. Meanwhile, the mutual exclusivity of these design endpoints keeps AR glasses in early-adopter phases.

What will it take to get over that hump and bring AR glasses to the mainstream? Will **Apple's** rumored glasses accomplish this? And how many years will this evolutionary process take? We'll answer these questions and others in this report through numbers and narratives.

As a bonus, we've included insights from AR glasses expert and The AR Show host Jason McDowall. He provides technical analysis of AR glasses' path to viable mass-market appeal; and the steps to reach the holy grail of *wearability*.

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# Key Takeaways

- **Though AR's attention and scale mostly reside on the smartphone, its true endpoints are headworn.**
- This is the AR modality that will unlock the technology's "native" potential as it offers line-of-sight orientation.
- Mobile AR has meanwhile achieved respectable levels of commercial success, such as AR advertising.
- Snapchat – the biggest beneficiary of mobile AR – even signals that it's an evolutionary step towards glasses.

- **AR glasses have already arrived meaningfully if considering their deployment in enterprise settings.**
- AR glasses' stylistic and wearability challenges aren't prevalent in the workplace, where sensibilities differ.
- There are also clearer ROI and business cases for enterprise AR, including productivity enhancements.
- Consumer AR glasses spending will eventually eclipse that of enterprises due to larger population sizes.
- That process will take several years to unfold, following common tech patterns of early-stage enterprise adoption.

- **ARtillery projects AR glasses revenue to grow from $822 million in 2019 to $13.4 billion in 2024.**
- Enterprise spending represents 98 percent of that total today, retracting to 90 percent by 2024.
- This is steep growth, as it starts with a small base and will be accelerated by an enterprise tipping point in 2022.
- Consumer spending growth will be accelerated by Apple's projected market entrance, also in the 2022 timeframe.

- **Apple's market entrance will lead to meaningful device sales for its own glasses and others (halo effect).**
- Though it will be the market leader, Apple's AR glasses will sell less than 5-million units in their first three years.
- This projection factors in historical growth for emerging and category-defining products like iPhone and Watch.
- Though growth will be steep, aggregate AR glasses sales in 2024 will be dwarfed by smartphone sales 2000 to 1.

- **As for smart glasses themselves, they could defy – or at least broaden – connotations with "AR."**
- Apple only aims for massive markets, meaning its AR glasses could align with sunglasses or corrective eyewear.
- This reality informs its feature set, possibly including HDR digital filters that improve or enhance human vision.
- Its glasses could also facilitate utilities such as local commerce (see project Gobi[ii]) and iOS notifications.
- It could also achieve sensor fusion with other wearables (AirPods and Watch) for holistic sensory augmentation.

- **Apple's V1 glasses could be described as "AR lite," evolving over several generations (like the iPhone).**
- Underlying optical and display technologies dictate that visual intensity and sleekness are mutually exclusive.
- Given this choice, Apple will opt for the former as it aligns with design sensibilities and larger markets.
- This will shift the industry's attention towards *wearability* as a core design principle for smart glasses.

- **Rather than graphically-rich glasses that get sleeker over time, the reverse evolutionary path will prevail.**
- This flips the model that prioritized graphical UX over hardware style and wearability (see Magic Leap).
- With the *wearability* principle in mind, technologies further down the stack will adjust to this target.
- This will include all parts of the AR value chain including optical technologies and display systems.

- **Speaking of the underlying tech stack, a largely under-appreciated set of technical barriers looms.**
- Primary components are optical and display systems, which have a direct impact on glasses quality and comfort.
- Quality refers to UX factors like brightness, field of view, and resolution, which represent sizeable challenges.
- Comfort refers to physical and social comfort, both requiring smaller glasses that defy needs of the optical system.
- Several technical approaches are being developed, each involving big tradeoffs (detailed later in this report).

- **These technical and practical barriers deviate from generalist media that paints a "blue sky" picture.**
- Though well-intentioned, this sets AR up to fail commercially by setting overblown consumer expectations.
- A "reset" is required for consumer viewpoints on realistic AR glasses that will arrive from Apple and others.
- That reset is already underway, considering the market correction from AR's circa-2017 hype cycle.
- Accurate expectations will ensure appreciation for the requisite steps and milestones in AR's evolutionary path.

# Introduction: The Endgame

Though AR's attention and scale have erstwhile resided on the smartphone, its fully actualized form will arrive in glasses form. This is the AR modality that will unlock its true potential, given that use cases will be more intuitive and positioned in users' line of sight.

Though that's the case, we don't mean to downplay the success seen in mobile AR. Though it will be eventually dwarfed by the value created by AR glasses, there have been respectable wins achieved in smartphone-based AR, such as **Snapchat's** AR lenses.

After accomplishing deep and frequent user engagement levels, **Snap** has attracted brand advertisers that want to expose their products and messaging with the same degree of immersive depth. We project AR advertising in the aggregate to reach **$8 billion** by 2024.[iii]

But even **Snap** admits that mobile AR is an evolutionary step on the path to AR glasses. This is why it simultaneously fuels mobile AR lens initiatives and wearable hardware. **Snap's** Spectacles aren't AR glasses but they represent an R&D effort to get a feel for the social dynamics of wearable tech.

"We believe that in order to envision this future of computing overlaid on the world, you really need to take the screen away that's cutting you off from the actual physical world, which the mobile phone does," **Snap's** Carolina Arguelles said at the AWE Europe conference. "Our investment in Spectacles is because we want to test, iterate, and understand what it means to interact with cameras when they're on your face. We want to know what good content is… How people interact with it… What they like… What should the UX be? "

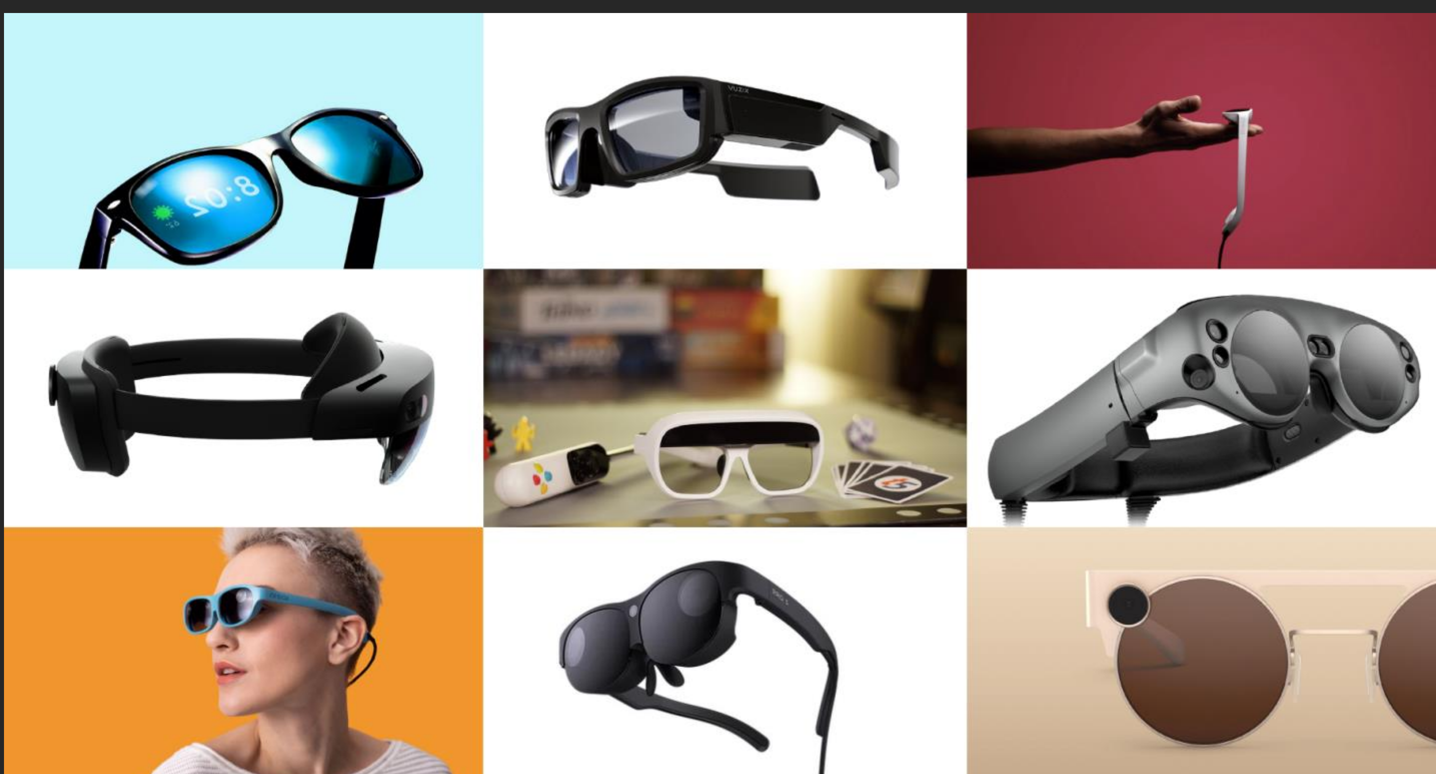


Image source: (from top left) Morning Brew, Vuzix, Nreal, Microsoft, Tilt Five, Magic Leap, Nreal, NuEyes, Snap.

# Consumer/Enterprise Divide

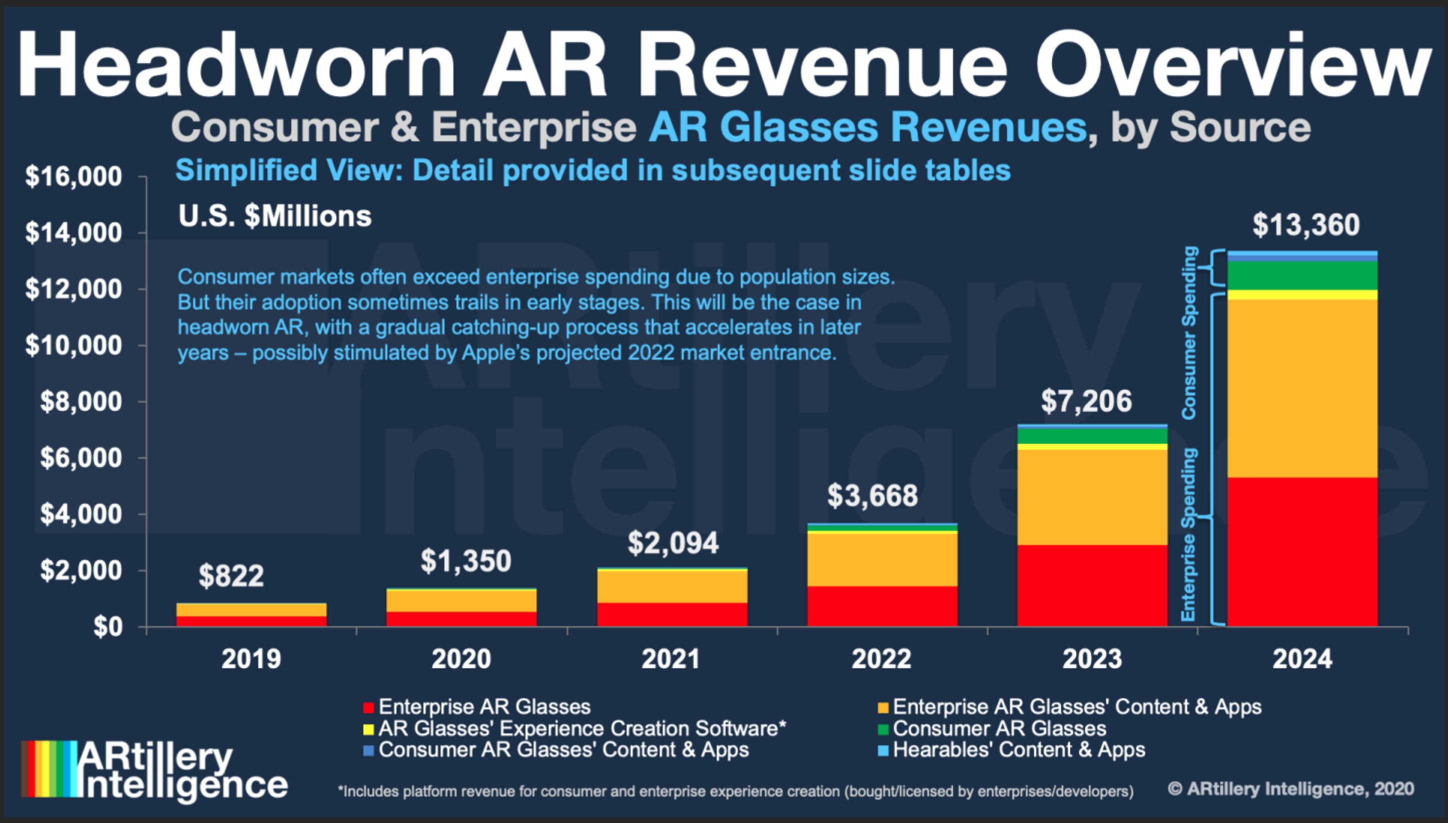
Though we used the term "eventual" above to qualify AR glasses' arrival, they've already arrived if you consider enterprise deployments. There, AR glasses' stylistic drawbacks aren't as much of an issue as in consumer markets. Form-factor issues still exist, such as comfort and heat, but these drawbacks are forgiven when sizeable ROI gains are at play.

For these reasons, enterprise spending dominates AR glasses. However, spending shares could eventually flip as AR glasses get sleeker and more commercially viable. Consumer markets are generally bigger than enterprise markets due to population sizes, but enterprise-spending often leads in early days of emerging tech. That trend is evident in AR.

To quantify that, ARtillery Intelligence projects AR glasses spending to grow from **$822 million** last year to **$13.4 billion** in 2024. Enterprise spending is **98 percent** of that total today, but will retract to **90 percent** by 2024, and continue to decline from there until consumer/enterprise trendlines intersect.

But that could take several years, not just due to requisite technical advancements, but also AR glasses acceptance. As seen from **Google** Glass' early consumer trials, cultural acceptance and comfort levels for face-worn hardware (with a camera, no less) is an uphill climb. This factor will supersede the technology itself in gating consumer AR penetration.

But there are also glimmers of hope. For example, history tells us that if anyone can accomplish that feat of mainstreaming emerging tech – or at least catalyze the process – it's **Apple**.



# Apple: The Wild Card

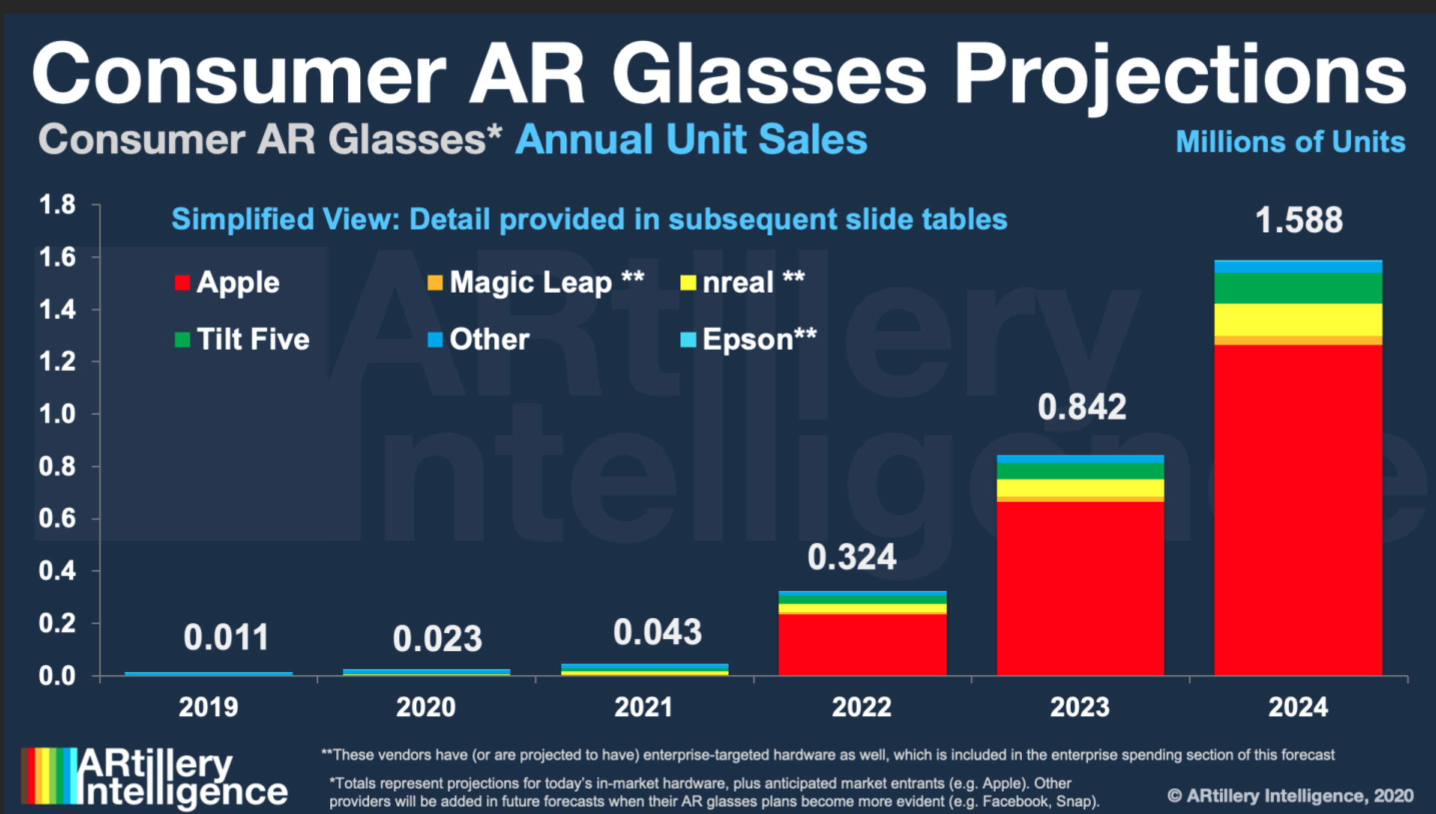
**Apple's** track record in mainstreaming emerging tech – also known as its "halo effect" – is the reason why you likely hear so much chatter about its rumored smart-glasses. The stakes are high for the AR industry, as **Apple's** eventual moves could accelerate the technology's ability to achieve scale.

But the question is, what's **Apple's** strategy? And what will its prospective glasses be and do? Starting with the former, **Apple's** AR glasses strategy is driven by similar factors as its wearables play that we've examined[iv]: to future proof its core hardware business in the face of a maturing smartphone market.

**Apple** AR glasses could accomplish this by both propping up and succeeding the aging iPhone. The former happens as it creates reliance on the iPhone for local compute. In other words, the iPhone gains importance – and user incentive to upgrade – if it powers your smart glasses.

An iPhone succession plan is meanwhile accomplished through a suite of wearables that replaces the collection of iThings at the center of our computing lives. That could mean line-of-sight graphics through AR glasses, which accompany spatial audio from AirPods PRO, and biometrics from **Apple** Watch.

This theory fits the profile for **Apple's** signature multi-device ecosystem play. Its marketing and product positioning will emphasize that the whole is greater than the sum of its parts, so you should own several devices. In this way, AR glasses will be a key puzzle piece in **Apple's** future road map. Like the iPhone, they'll start slow, then scale up rapidly.



# Reconceptualizing AR

After covering the *why*? of **Apple's** AR glasses the remaining question addresses the *what*? What will they look like, and what will be the primary feature set? We don't know for sure, but many clues point to the likelihood that **Apple** will eschew common connotations with AR experiences.

In other words, **Apple** likely won't launch AR glasses — at least in version 1 — that employ "heavy AR." This is world-immersive AR that has spatial and semantic understanding of its surroundings. This longer-term vision for AR is all about graphics that populate your field of view in dimensionally-accurate ways.

But to achieve these functions, there are design tradeoffs such as bulk and heat, which would deviate from **Apple's** style and design sensibilities. So in the sliding scale between sleek glasses that power "light AR"; and bulky hardware that powers "heavy AR," **Apple** will likely lean towards the former.

The first clue for this theory is the state of the underlying technology. It's not to the point where sleekness and graphical intensity are possible in the same device. The second clue comes from **Apple's** size and its resulting fiduciary drive to pursue massive markets.

Given that reality, "light AR" glasses have a much larger potential addressable market than bulky sensor-laden ones do, as the latter only appeals to a subset of technophiles. **Apple's** mass-market requirements could lead it to AR hardware that is more along the lines of corrective eyewear or sunglasses.

In other words, eyeglasses and sunglasses are much larger markets than AR glasses. In fact, **Apple** could enter the **$200 billion** corrective eyewear market. AR features will include line-of-sight notifications that integrate other **Apple** apps, or biometrics from your **Apple** Watch.

Moreover, as noted, **Apple** will broaden the concept of "augmentation" beyond the AR world's current connotations. So instead of cartoon monsters, digital "layers" will be things that generally help people see better – either in a corrective sense or with digital filters that "brighten" your day in various ways.

Other clues indicate practical mass-market functions, such as the integration with **Apple's** "project Gobi[v]." This involves retail point-of-sale codes that unlock product promotions or **Apple** Pay. This not only has mass-market applicability but could align well with a post-Covid world of "touchless" retail.[vi]

There could also be spatial audio integration with AirPods Pro, given Apple's classic multi-device ecosystem approach. This could involve an audible "notification layer" that joins its visual counterpart. Use cases could include identifying people or real-time foreign language translation. These could be widely-used apps.

All of the above could represent **Apple's** first step into sensory augmentation. Like the iPhone 1's long evolutionary path to the pocket supercomputer we know today, "Apple Glass" will grow from simple augmentation to eventually achieve the AR formats that are seen more in the realm of science fiction.

Image source: Morning Brew

# Video Companion

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# AR’s New Target: Wearability

In line with **Apple’s** projected approach, a realization has begun to sink into the AR sector. After years of excitement over the impending era of world-immersive AR, there’s a growing consensus that the technology is still far from bringing that dream to a pair of glasses that most people will *wear*.

This comes down to a classic design tradeoff. Visually immersive and contextually-aware AR glasses like **Magic Leap** One and **Microsoft** Hololens 2 require optics whose power consumption and heat dissipation necessitate bulky headgear, rather than anything you’d consider “eyewear.”

At the other end of the spectrum is hardware such as **North** Focals. Inverse to the above examples, these lack immersion and contextual awareness, but they’re stylistically-viable. Between these endpoints is a sliding scale where we see glasses like **Nreal** Light.

Throughout this progression, there was one common point of value: *mobility*. Whether it’s calls, texts, email, web browsing, summoning Uber or swiping Tinder, mobility has sustained as the core value proposition — albeit increasingly dressed in incremental value over time.

Applying that principle back to AR, could *wearability* be the next era’s mobility? And if so, should it represent AR glasses’ V1 design target, which then evolves over time towards advanced AR functionality? That’s opposed to starting with advanced AR then sizing-down over time towards wearability?

Evidence in today’s market support this play. As examined in the previous section, the latest signals for **Apple’s** AR glasses indicate regular glasses that eschew a **Magic Leap**-style AR experience in favor of simpler optical enhancements like helping you see better.

## Next Mobility

The North approach could be right for today’s AR glasses if viewing product evolution in light of historical examples. In other words, consider (again) the iPhone 1 which launched with relatively few features and apps, no GPS, low-quality camera, and other gaps that were gradually filled.

Going back farther, smartphones didn’t start with the iPhone, as earlier iterations from RIM and Windows Mobile let you make calls and send e-mail on the go. And feature phones before them gained rapid ubiquity with the simple value proposition of letting you make calls or send texts from anywhere.

Image Source: Bram Van Oost

# Design Target

These concepts have been bouncing around in industry discussions, events, and ongoing rhetoric of late. But for us, it coalesced during a recent discussion with **Ostendo** VP Jason McDowall. You may know McDowall as producer and host of the AR Show Podcast.[vii]

He approaches this discussion in light of the novel display and optics that **Ostendo** develops. With the wearability principle in mind, **Ostendo** is betting on a sleeker form factor for AR glasses that emerge and scale in the near-term as a function of mainstream consumer viability.

On the enterprise side, McDowall believes AR glasses will verticalize to some degree. In other words, one monolithic Hololens that's used across manufacturing, medicine, and education, could give way to glasses that are streamlined and purpose-built for the nuances of each field. The AR market isn't big enough yet for that purpose-built approach, but it will someday be.

Whether it's for consumers or enterprises, the point is that all-day wearable displays need to have UX endpoints well in mind, as they impact key development decisions. In other words, technical approaches can deviate widely in the quest to manipulate photons to render imagery optimally to the human eye.

"We're fundamentally providing a set of capabilities that unlocks the level of wearability that's not yet been achievable," said McDowall. "And it's based on the way that we're generating these photons, and conditioning and preparing them to be used within the context of AR glasses."


Image Source: Nreal

# Tech Stack

Going deeper, one of **Ostendo's** differentiators is LED micro-displays whose panels vertically stack red, green and blue pixels, rather than place them side by side. This lets it fit more pixels onto a display and achieve full-color and higher pixel density with less volume.

"There's a huge advantage to having them vertically stacked when making tiny pixels," said McDowall. "Because the display is so close to your face, you need densely-packed pixels to generate an image that matches human visuals. Vertically stacking also achieves more efficient integration with optics."

Speaking of efficiency, **Ostendo** places a graphical processing unit (GPU) on the base plane of the display panel. This achieves efficiencies that aren't seen when a GPU is further upstream to process graphics and send photons along to be channeled into a display.

The upstream GPU still exists, but the additional computing layer on the display allows it to be responsive to eye movement. This lets the display operate on compressed input, rather than driving all pixels at full color all the time, which can be wasteful in terms of producing heat and hardware bulk.

This approach is analogous to a system-on-a-chip architecture that achieves greater efficiencies in your smartphone by having integrated GPU, CPU, modem, etc. **Ostendo** similarly combines functions to process full-color light into a single chip to match the capabilities of the human visual system.

"One key to crafting a truly wearable display is recognizing that the goal is to couple information ultimately to our brain," said **Ostendo** founder & CEO, Dr. Hussein El-Ghoroury. "To do this, we have to match the movements and capabilities of the human visual system, and only put visual information where it's useful."


Image Source: Nreal

# Smarter Glasses

All of the above is in **Ostendo's** DNA, given El-Ghoroury's background in military-grade satellite communications as well as consumer cellular technology. From these and other roles, he's developed a keen eye for mobility's evolutionary path towards wearability.

Speaking of evolution, McDowall identifies three pillars for AR's longer-term viability as the next personal computing paradigm: *hands-free, contextual insight,* and *Just-in-time*.

The *hands-free* pillar we've covered above in the wearability principle. *Contextual insight* is the "defining lever of value" says McDowall, involving situationally-aware content that can be visual, audible, or haptic. And the *just-in-time* pillar is all about having it delivered intelligently when it's needed.

McDowall and his colleagues are confident we'll get there, and they have factored that future into **Ostendo's** road map. The next few years could even see important milestones towards that holy grail: a device that's both wearable and fully immersive beyond what Hololens 2 or **Magic Leap** deliver today.

But to run that marathon requires revenue to reinvest, hence wearability as a near-term design priority. Here, irony lies in the term "smart glasses" itself. Taking the term literally, do we first need *smarter* glasses… as in, slightly-smarter tech-fueled versions of today's corrective eyewear?

"A good way to get consumer wearable displays into the mainstream is to start with the functionality of glasses," said McDowall, "and make them a little bit better… glasses *plus.*"

Image Source: Tilt Five

# The Path to Mass-Market AR

Building from the above analysis of **Ostendo's** approach, it's time to go one level deeper. We invited **Ostendo's** Jason McDowall to provide insights, including in-depth technical and practical perspective on AR glasses' path to mass-market success.

The next few sections do just that by exploring the barriers and potential solutions to making consumer-grade AR glasses that mainstream consumers will actually wear. He starts on the next page by defining underlying technology challenges and the common assumptions used today to address them.

With that backdrop, McDowall then details the display and optical systems and various approaches that are being applied, including their pros and cons. He also takes a contrarian view to some commonly held beliefs, and concludes with a recommended path to idealized outcomes in AR glasses.

As a disclaimer, the level of technical nuance in the next several sections is intermediate to advanced at times. For those without technical knowledge, follow the overall story arc without getting too bogged down in technical terms. AR's broad technical challenges and timelines should be the predominant takeaway.

Image Source: Magic Leap

# What's the Holdup?

Starting at the beginning, AR's story relates to VR, which had a false start in the 1990s before receding to research labs. Now we see a small, but healthy market for VR devices, software, and services focused on entertainment, training, education, and clinical uses.

But it took two decades and significant advancements in technology (including processors, displays, optics, and sensors... courtesy of the smartphone revolution) before achieving this level of commercial success. Given the unimpressive adoption of **Google** Glass and everything that came since, should we assume that AR glasses need another few decades to reach broad adoption?

It's clear that attempts to date have fallen short. Over the past seven years, we've seen several consumer and enterprise-grade AR glasses from **Google**, **Microsoft**, **Magic Leap**, **North**, **Meta**, **ODG**, **DAQRI**, **Vuzix**, and others. Not one has achieved meaningful scale, while several don't even qualify as "glasses."

Speaking of which, we'll pause for definitions: Throughout this analysis, we'll use the term "AR glasses" broadly to reference head-worn devices that allow you to directly see the real world coupled with digital content. That could mean basic 2D content or more immersive 3D experiences tied to the real world, sometimes called *Mixed Reality*.

Here, we sometimes forget the difference between "can" and "will." Can these devices be developed to display digital content? Yes. Will they be (or have they been) adopted to any meaningful degree? No. They're not yet *wearable* enough for consumers to want them en masse. Even for enterprises, where the ROI is compelling across several use cases, adoption is low relative to ubiquitous products.

Some may argue that it's too early to tell for **Microsoft** Hololens 2. But the fact is that it falls short in a few key dimensions. We'll get into that. And there's hope that **Apple** and **Facebook** are on the cusp of something worthy. But release dates for their respective AR hardware are still a few years away.

Image Source: Microsoft

# Displays and Optics are the Biggest Barriers

Many billions of dollars have been spent in AR research by tech companies who are otherwise very successful. It's not for lack of investment or engineering talent that the industry has fallen short, but for a lack of innovation – specifically around displays and optics.

Displays and optics in AR glasses have an enormous impact on visual quality and device comfort. The visual quality of a wearable display includes the quality of the digital imagery (color, brightness, field of view, and angular resolution) as well as that of the real world (obstruction, distortion, and dimming). Device comfort includes physical comfort (weight, heat and ergonomics) and social comfort (fashion sensibilities and eye contact). Getting these factors right is necessary for AR glasses to become truly wearable and broadly adopted.

Despite some beautiful artist renderings, light does not magically emerge from every part of the lenses of today's AR glasses, nor will they in **Apple** or **Facebook's** eventual entries into the market. In fact, part of the challenge for AR glasses is that we don't look directly at the display as we do when looking at our flat-panel TVs and mobile devices. Instead, we look through a clear lens at an (ideally) undistorted and undiminished view of the real world. The display sits somewhere off to the side, and the light needs to be redirected through, or reflected off, the lens and into our eyes.

Plus, when talking about actual glasses and not headgear clamped to our heads, the whole contraption needs to rest on the bridge of our delicate noses and ears, and against our sensitive skin.

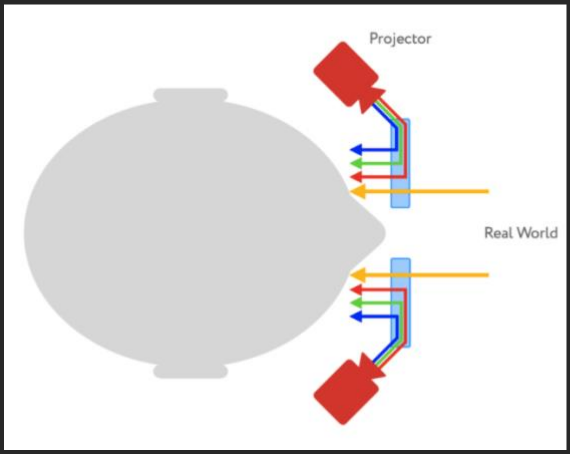


Image Source: Jason McDowall, Ostendo

## Historical Parallel

In the AR glasses attempts to date, the industry tried to reuse 40-year-old display technology that was built for a different purpose... and it's not working. These efforts are equivalent to integrating an old CRT tube monitor with a computer and keyboard, then calling it a laptop. While such devices did meet the loose definition of a portable "laptop" computer, they barely scratched the surface of the potential benefits of such devices.

It was the invention and refinement of LCD display technology that was necessary for the advancement and wide-scale adoption of laptops (and ultimately smartphones). For truly wearable and broadly-adopted AR glasses, the same type of significant and "native" force multiplier in display and optics is needed.

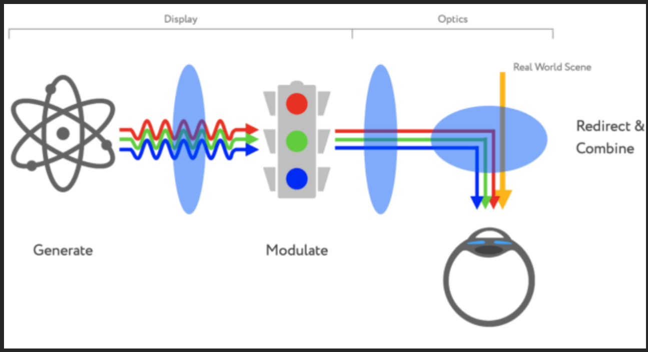


Image Source: Jason McDowall, Ostendo

# Hard Problems and Current Assumptions

So much of AR glasses' visual quality and device comfort is driven by the amount of energy and space needed to generate, modulate and redirect light into our eyes. Generating and modulating are typically done by a display system, while redirecting is done by optical elements.

To break this down a bit further, Displays and optics affect visual quality in terms of field-of-view, angular resolution, brightness, color uniformity, depth of focus, and visibility of the real world. The size, weight, and physical positioning of the optics affect device comfort. Device comfort is further impacted by display size and power efficiency, which determine things like heat and battery needs (more bulk).

With such a massive impact on AR glasses' wearability, displays and optics must work in close concert. And because the display sits so close to our eyes, the pixels need to be tiny (≤ 10 µm). Otherwise, we'll see gaps between pixels, and angular resolution will be too low.

Because the real world is the background, the display needs to be bright (> 5,000 nits to the eye). Otherwise, the image will be washed out when we are in a bright room or outside. And because we want to use AR glasses for more than a few minutes at a time, the device needs to be lightweight and energy-efficient (weight ≤ 65 g, volume ≤ 50 cc, and support hours of active use). And because we care what others think of us, the glasses need to look "normal" and reflect personal style.

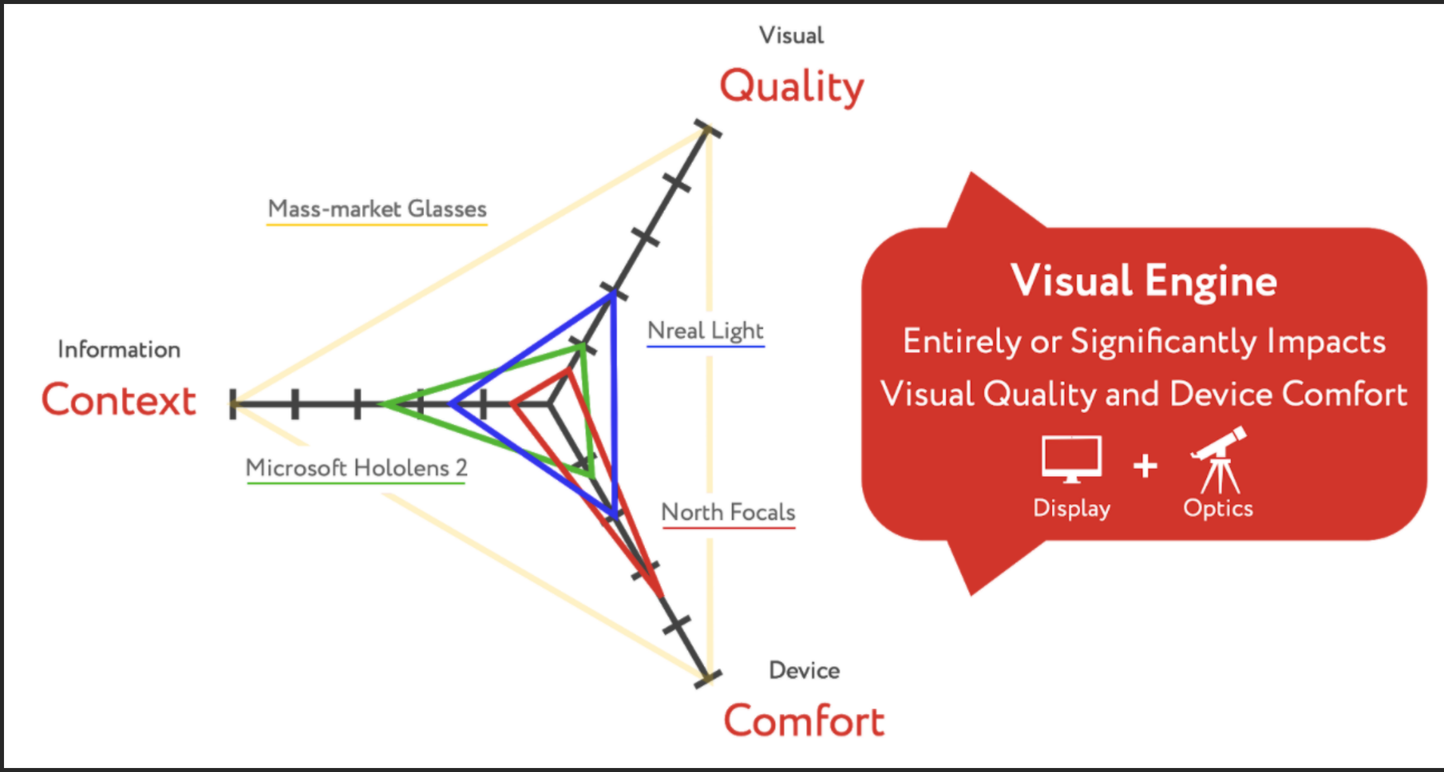


Image Source: Jason McDowall, Ostendo

# Assumptions & Implications

In attempting to overcome the above practical and design challenges, the AR industry has collectively made a series of assumptions:

**1**. **Display technologies are dumb, because they need lots of help conditioning the light to be useful.**
**2**. **Optics must be complex, inefficient, and/or bulky to compensate for dumb displays.**
**3**. **Unique product variations must be few, to compensate for complexity of the optics.**
**4**. **Displays must be bright to compensate for inefficiencies in the optics and limited product variations.**

We'll tackle these assumptions one by one, but first some background...

Despite billions of dollars invested by the world's biggest brands and some crafty startups, AR glasses have not achieved meaningful traction. The predominant approach in the AR industry is to take dumb displays and pair them with complex and inefficient and/or bulky optics. To understand why today's displays are dumb and optics are inefficient and/or bulky, let's break down the problem and take a closer look at the current solutions.

## Spray and Pray

In the quantum realm, a single element of light – a photon – is born from an electron. An energized electron will emit a photon when the electron returns to a lower energy state. The direction the photon begins its journey is random. The result is that the light is spread out as it emerges from its source within a display. With our flat-panel TVs or mobile devices, this attribute is a feature: we can view the content from a wide variety of angles, which is helpful when a group of people gathers for a watch party (pre-Covid of course).

However, when you wear a display on your face, there's only one person viewing the content and she doesn't look directly at the display. As noted earlier, the display sits off to the side. Somehow, we have to channel the light from the display and combine it with the light from the real world, while keeping the device small enough to be comfortable (physically and socially). Any light that doesn't reach our eyes is wasted... and wasted light contributes to more heat, bigger batteries, and bigger device size.

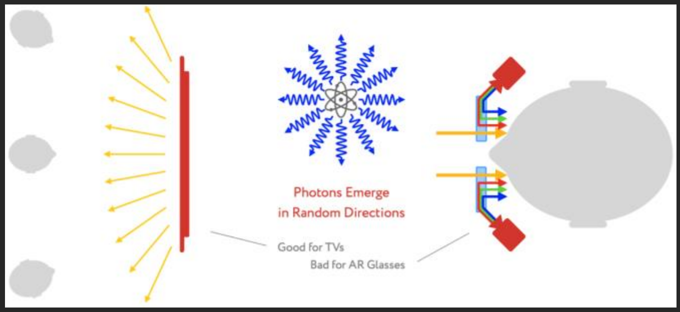


Image Source: Jason McDowall, Ostendo

# Corralling the Light

In AR glasses, the “feature” of spreading light becomes a sizeable bug. This brings us to the **first of four assumptions** listed above: *Display technologies are dumb*.

Dumb displays spew light where it’s not useful, either resulting in wasted light (which equates heat and battery size) or wasted space (which equates to added weight and bulk).

This “bug” in today’s display technologies is solved by adding optical elements such as lenses and reflective surfaces. “collimating optics” catch the light as it comes out of the display to point it in a useful direction. “Useful” in this case means pointing towards the lens that’s used to see both the digital information and the real world. These techniques aren’t perfect, and the more light we try to catch and redirect, the bigger the optical elements and the lower the overall efficiency.

The challenge of redirecting light within see-through wearable displays gets harder from there. After pointing the light in a useful direction, the light then needs to be inserted into the see-through lens. These “input coupling optics” take the light from the display and get it traveling into the side of the lens so that it can be redirected into our eyes at the right spot.

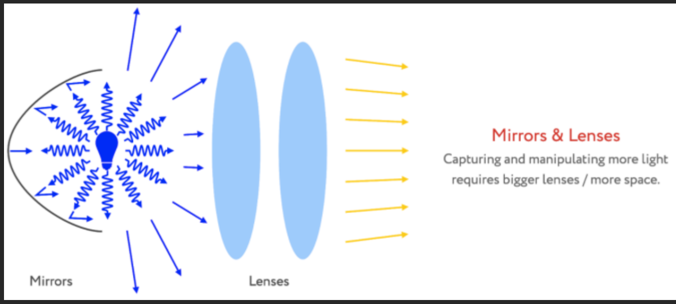


Image Source: Jason McDowall, Ostendo

The effectiveness and efficiency of “in-coupling” light depends on the type of lens the light is going into. These “combiner optics” are typically semi-transparent curved mirrors (used by **Nreal**) or diffractive waveguides (used by Hololens and **Magic Leap**). Curved mirrors are relatively efficient at in-coupling and out-coupling the light, but they’re bigger and bulkier. There’s a more nuanced spectrum of techniques, but the above two approaches are the most common endpoints.

To their credit, diffractive waveguides are much thinner. But unfortunately, they’re also much less efficient, more complex, expensive, and fragile. Here, input coupling is a sizable challenge. On the way in, the light gets bounced in many different directions, most of them harmful to the visual experience. Further challenge is presented by the fact that the light in-coupling area is typically much smaller than the display; this difference means more light manipulation is required, which necessitates more optics, bulk, and inefficiency.

Companies such as **WaveOptics**, **DigiLens**, **Dispelix**, **Holographix**, **Vuzix**, **Microsoft**, and **Magic Leap** develop or license diffractive waveguides. **Lumus** pursues a slightly different approach: reflective waveguides, which are used in the latest AR hardware from **Lenovo**. These are more efficient at coupling light, but more complex to manufacture.

Due to their thin profile, these types of waveguide technologies have been deemed the best hope of achieving wearable displays that look like normal glasses. This consensus exists despite inefficiencies of the display and other optics in the system.

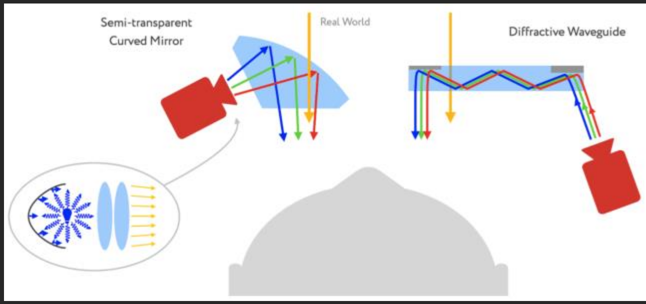


Image Source: Jason McDowall, Ostendo

## One in a Million

That brings us to the **second assumption**: *Optics must be complex and inefficient, or bulky, or both – to compensate for “dumb” displays.*

The AR industry expects that wearable displays will be the primary interface for heads-up, hands-free, just-in-time, contextual insight. The expectation is that this won’t be a niche product, but one embraced by billions of people. In the smartphone era, these billions have been satisfied with a small assortment of unique product variations (think: iPhone SE, Plus and Pro variations). Relatively common use cases and hand sizes have made this approach feasible.

But variations in our eyes and noses raise issues in designing wearable displays to support billions of people. Most humans’ eyes are spaced about 6.4 centimeters apart, plus or minus one centimeter. This may not seem consequential, but when trying to align tiny displays so close to our faces, it can be the difference between digital image clarity and incomprehensiveness.

## Eyeing the Future

That brings us to the **third assumption**: *Unique product variations must be few, to compensate for complexity of the optics.*

Due to cost and other logistical reasons, AR glasses manufacturers are compelled to limit AR glasses variations to a few models. Several variations can lead to inventory headaches, especially in early days when sales penetration isn’t great enough to financially justify it.

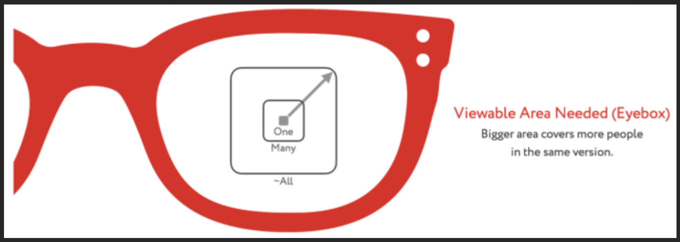

Image Source: Jason McDowall, Ostendo

But if the eyewear industry can sell **$150 billion** in products each year with mass customization, the tech industry may be able to figure it out. **Apple** is already showing some movement in this direction by offering 18 sizes for its clasp-less Solo Loop watch bands.

To otherwise accommodate variation while maintaining a one-size-fits-most (or two-sizes-fit-all) approach, virtual images must be viewable from a wide range of positions behind the lens. We call this area the “eyebox,” and the implication is that it must be large.

To accommodate a large eyebox, the favored waveguide approach is to make the display appear in more than one spot at the same time. This “pupil replication” technique is an impressive engineering accomplishment, but it compounds display system requirements. For example, the display must be much brighter to account for light that’s spread across multiple locations. In this approach, the light from a small display is crammed into an even smaller opening (in-coupling optics) and distributed across several exit spots to make the display viewable from a larger eyebox.

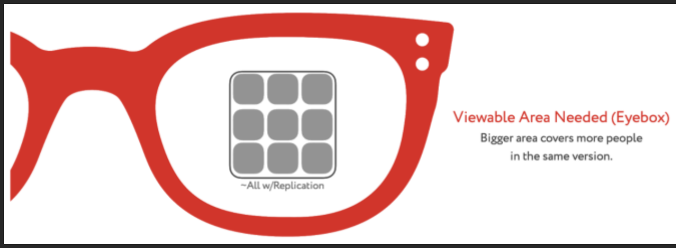

Image Source: Jason McDowall, Ostendo

## Bright Future

To compensate for the light that's lost when expanding the viewing area in the above ways, we get our **fourth and final assumption**: *displays must be extremely bright to compensate for the inefficiencies of the optics and limited product variations.*

How inefficient? For diffractive waveguides, more than **99 percent** of light emitted from the display doesn't make it to our eyes. To get an image that is viewable outdoors, a pupil-replicating waveguide needs several million nits of brightness. By comparison, the display you're using to read this report produces a few hundred nits. So the industry-favored waveguide approach needs light that is at least four orders of magnitude brighter than your phone or computer screen…in a device that you wear on your head.

So what's the answer? Is it laser scanning displays or emerging microLED displays paired with diffractive waveguides? Or are there alternative approaches? We'll explore these questions next.

Image Source: NuEyes Technologies

# Micro-LED & Laser Scanning

Summarizing where we've been so far, to build truly wearable, mass-market AR glasses, it's imperative to use the right combination of displays and optics. These two main factors determine visual quality (both the digital image and the real world) and device comfort (both physical and social comfort).

However, current consensus is to use highly inefficient and/or bulky optics paired with a dumb display that needs to be exceptionally bright, as explored in the previous section. If we follow this consensus, where can we find such an exceptionally bright display? There are a few options that continue to evolve.

## Organic LEDs

When it comes to head-worn displays, microOLED (organic light-emitting diodes) can work well for VR because it's fully enclosed. But even recent advancements from companies such as **Kopin** don't deliver enough brightness for AR glasses with diffractive waveguides. Remember the required brightness levels quantified in the previous section.

But there are ways around this challenge. For example, **Nreal's** MicroOLED shows that it can be viable with more efficient – though bulky – curved mirror optics. But this still comes with downsides such as the inability to use glasses outdoors or make eye contact.

## Lasers

Meanwhile, lasers can be exceptionally bright – even enough to compensate for the inefficiencies of diffractive waveguides. But they don't generate individual pixels on their own. To get full color across the entire viewable area requires multiple lasers (at least three for the RGB spectrum) to simulate pixels by moving in a scanning pattern while light intensity adjusts dynamically.

Image Source: Microsoft

**Microsoft** Hololens 2 uses a laser scanner paired to a diffractive waveguide with disappointing results in visual quality. North Focals use laser scanning with different optics. The company was planning a second version with an improved visual experience, but those plans were sidetracked when **Google** bought North, with little indication of future plans.

Display and optics expert Karl Guttag predicts that laser scanning displays will never achieve the requisite visual quality within a wearable form factor. Some disagree, but Guttag argues that while laser scanning looks very promising at first glance, like an iceberg, big challenges await below the surface.

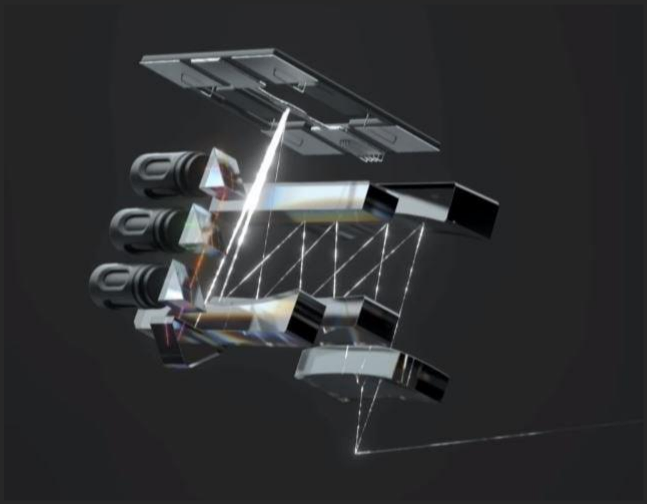

Image Source: Microsoft

## MicroLED Lights the Way

MicroLED is an emerging technology for generating and modulating light. Similar to organic LEDs introduced above, inorganic LED displays are "emissive," meaning they don't need a separate light source, as required by DLP (projector) or LCD displays. They're also more compact, efficient, and last longer while achieving brightness levels that are 1000s of times that of OLED displays.

On the surface, microLEDs seem like a perfect solution for wearable displays. However, the technology isn't mature yet. To get highly technical for a moment (non-technical readers can skip to the next paragraph), the challenge is making LED pixels smaller than 10 µm and arranging them in a grid pattern, which is compounded by the need to make each color component ~3 µm so the overall pixel can be 10 µm. Instead, to achieve full-color today, multiple single-color panels would need to be used and arranged to merge their light, requiring ~3 times the power and ~8 times the volume of a single full-color panel. This is a significant barrier when device comfort is paramount.

Companies are exploring ways to assemble single panels with full-color, but manufacturability is a key hurdle. The approach that has the most potential to scale while achieving a reasonable cost is called "monolithic," meaning the display chip is built up layer by layer using standard semiconductor tools and techniques. **Plessey** is a microLED display company pursuing this approach. It still hasn't achieved full color, and it's a big jump from creating a one-color panel to a full-color panel. However, its approach is promising enough that **Facebook** effectively took the company off the market in a recent manufacturing partnership.

## Even MicroLEDs May Not Be Enough

Even a full-color microLED microdisplay, once available, will fall short of the ultimate goal of high visual quality and device comfort when it's paired with complex and inefficient and/or bulky optics. There are a few reasons for this.

First, the combiner optic is still going to be bulky (curved mirror) or grossly inefficient (diffractive, pupil-replicating waveguide). In search of a better solution, some upstarts, such as **Tooz**, **Oorym**, and **LetinAR**, are pursuing alternative combiner optic designs, albeit with some tradeoffs.

Second, the light coming from the display still spreads out, and it needs to be conditioned to get it into the lens. For diffractive waveguides, there's an extra challenge of cramming all of the light from the relatively larger display into the smaller input coupling area as explored earlier. Even a MicroLED may not be enough to deliver sufficient brightness to make the device usable outdoors, much less a truly wearable, mass-market device.

Are we then stuck waiting 20+ years for the technology to evolve and meet our goals under these current assumptions?

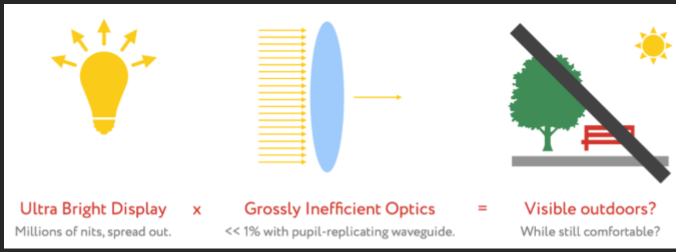

Image Source: Jason McDowall, Ostendo

# Flipping Assumptions

Picking up where we left off in the last section, the challenges facing AR glasses design continue to be vexing and nuanced. And many of those challenges continue to be viewed through the lens (excuse the pun) of the AR industry's common assumptions.

Here are those assumptions again for quick reference...

**1. Display technologies are dumb, because they need lots of help conditioning the light to be useful.**

**2. Optics must be complex, inefficient and/or bulky to compensate for dumb displays.**
**3. Unique product variations must be few, to compensate for complexity of the optics.**
**4. Displays must be bright to compensate for inefficiencies in the optics and limited product variations.**

But what if these assumptions are backward? What if we made displays smarter and the optics less complex? What if we can accommodate a wider variety of human physiology and personal styles? What would that look like?

| | Old Assumptions | New Assumptions |
|---|---|---|
| Displays must be | Dumb and Extremely Bright | Smart and Efficient |
| Optics must be | Complex and Inefficient/Bulky | Simple, Efficient, and Slim |
| Product Variation must be | Limited to 1 or 2 | Wide |

Image Source: Jason McDowall, Ostendo

# A New Type of Display

Flipping common assumptions implies a new type of display technology, which is no small feat. There's a reason why big tech has either stayed away from, or struggled to produce, a breakthrough in display technology. It's notoriously difficult.

In fact, over the past 150 years, the fastest time from conception to commercialization of a new display technology was 20 years. That was DLP, which is now commonly used in theater projectors, but also in some head-worn devices. Getting a new display technology to fit inside of a device that can be worn on the head can take decades. MicroLED is following a similarly slow path and still has some fundamental challenges to meeting goals, but we're talking about something even beyond microLED. What does that look like, and how do we get there?

# Purpose-built

To circle back to an earlier point, any light that doesn't end up in our eyes is wasted. And wasted light is wasted energy, which impacts heat, size, and aesthetics. This is the reason for all of the extra optics and effort to corral and condition light in head-worn displays.

We can take this notion of wasted light one step further if we consider the needs of the human visual system. We perceive most of the color and high-resolution detail only through densely packed sensors (cones) at the very center of our eyes. The rest of our vision is primarily covered by different light sensors (rods), which are good for low-light and motion sensing.

Furthermore, the brain stitches together information to form our perception of reality. The brain is telling the eyes to jump around from spot to spot to fill in details, in what's called a saccade. And it does this several times per second. The brain plans ahead, ignores the moments when the eyes are in a saccadic motion, and then backfills the information after the eyes come to a rest. And in doing all of this, it does a brilliant job of taking in a few kilobits of information, and convincing us that our entire visual field is colorful, high resolution, and always up to date.

This means that full color, high-resolution light that hits the low-resolution sensor in our eye is essentially wasted. Light that hits the eye during saccadic motion when the brain ignores input is likewise wasted.

This thinking drives foveated rendering in VR devices to reduce the amount of computation needed to render an image. The same insights can be extended to displays. Varjo has applied a simplified version of this concept to its VR device, and Avegant is pursuing a foveated display for AR. Its demo is quite impressive.

Although motivated by the right insights, these approaches still struggle to achieve our ultimate goal... wearability.

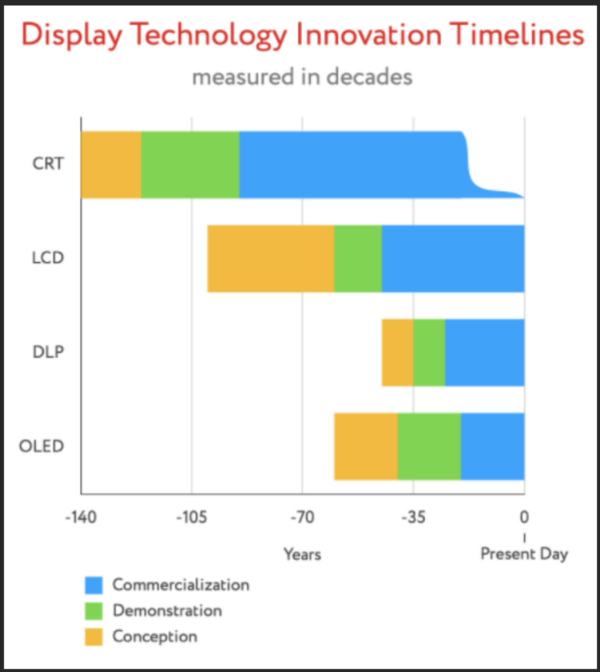


Image Source: Jason McDowall, Ostendo

## Holistic Approach

If the goal is wearability – again defined by visual quality and device comfort – the problem can't be effectively addressed as a collection of discrete problems pursued by independent teams. This divide-and-conquer approach can work brilliantly in software but face-worn hardware requires a holistic approach.

Starting with the needs of the human brain – outlined on the previous page – and appreciating the implications of a truly wearable form factor, an interdisciplinary team could design a different kind of display. And if we had a different kind of display, we could design a different kind of see-through combiner optic that matched that display.

## Integrated Systems

An ideal display wouldn't just spew light everywhere, relying on external optics to condition the light for insertion into the lens of the glasses (the combiner optic). Doing so takes up space, wastes light, and can affect the visual quality. Instead, the display would pre-condition the light before it emerges from the panel. And each pixel would be pointed in exactly the right direction for the light to be efficiently inserted into the combiner optic. This would allow the display to be directly coupled to the lens of the glasses, which is much more space and energy-efficient.

Furthermore, this ideal display would be a thin, full-color, microLED-based display. The bright, tiny pixels would be driven by an integrated image processor that can dynamically adjust the content across each pixel to match what our eyes perceive in each moment (per the brain dynamics explored above). That becomes more powerful when paired with eye-tracking technology that's available today.

All of this functionality in the display would be integrated using a system on a chip (SoC) approach. As noted earlier, this is the same approach that creates integrated and highly-efficient operations in a small package in your smartphone. It would be monolithically constructed using standard semiconductor tools and techniques, enabling it to be manufactured at scale and reasonable cost.

Paired with this display would be a new type of combiner lens that incorporates the benefits of classic curved mirrors and waveguide optics: an efficient light conductor with a slim profile that can be shaped to conform to our faces. This ideal lens would be cost-efficient to produce and accommodate our unique physiology and vision correction needs.

This gets back to the assumption of limited product variations. As noted earlier, if the eyewear industry can sell **$150 billion** in products each year with mass customization, the tech industry can do the same.

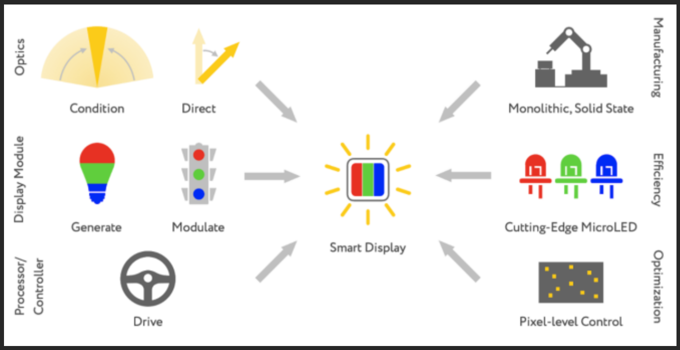

Image Source: Jason McDowall, Ostendo

# Companion Device

Maximizing physical and social comfort, the ideal display and lens would be integrated into a pair of glasses that serve as a *companion* to a smartphone. We already carry a device that can do the heavy lifting for computing and communicating the information to be displayed.

Conversely, there's little benefit, and ample detriment, when attempting to cram all of the capabilities of the phone into the glasses within the next few years. Mass-market wearable displays will instead *extend* the capabilities of smartphones for the foreseeable future.


Image Source: Morning Brew

# Final Thoughts: Baby Steps

If the technical deep dive in the previous several pages says anything, it's that AR's realistic challenges deviate from its "blue sky" public persona. Generalized editorials by non-AR professionals tend to future-gaze without perspective or reference to these technical realities.

Talking to AR practitioners in areas like optical systems and display technologies conversely evokes a sobering reminder that the dreams portrayed in the above editorials are years away. Could this set AR up to fail commercially as consumer expectations get overblown?

If public perception of AR's arrival and abilities can be adjusted, its nearer-term manifestations will be appreciated more as *evolutionary* steps. That expectation-setting has already begun if you consider the market corrections that followed AR's circa-2017 hype cycle.

As for those "nearer-term manifestations," events like **Apple's** market entrance could be meaningful. "**Apple** Glass" won't involve visually intensive experiences. But it could feature elegant "augmentations" of your sensory perception.

As noted earlier, that could include the act of improving human vision in corrective and enhanced ways. Dynamic filters could brighten your day while Watch (biometrics) and Airpods (audible) integrate for a more holistic UX. Simple and creative experiences like this sidestep AR's prevailing technical barriers raised in the previous sections, meaning they could be more attainable in the near term.

Meanwhile, adjusting expectations for AR's near-term could avoid disappointment and instead let us appreciate the technology's milestone-laden evolutionary path as it unfolds.

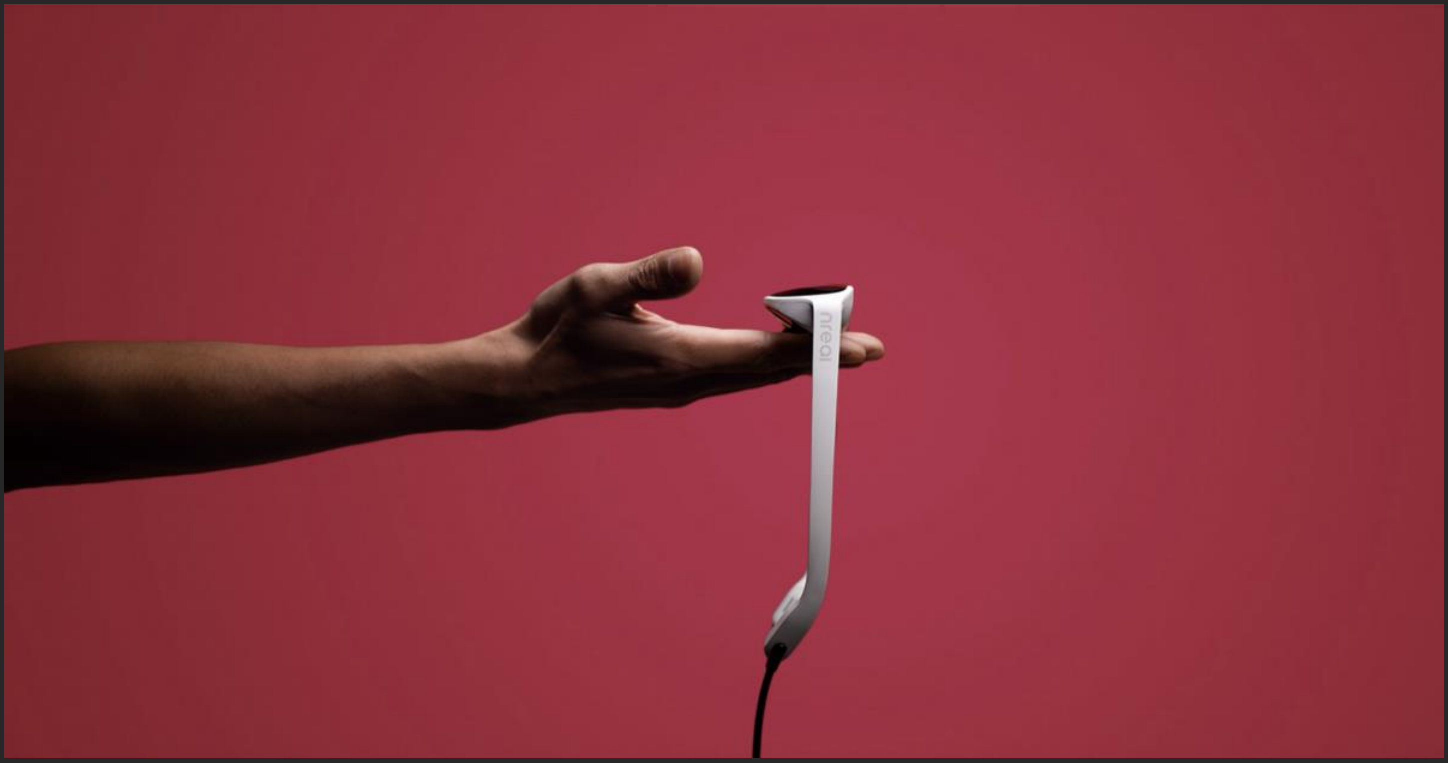


Image Source: Nreal

# Key Takeaways

- **Though AR's attention and scale mostly reside on the smartphone, its true endpoints are headworn.**
- This is the AR modality that will unlock the technology's "native" potential as it offers line-of-sight orientation.
- Mobile AR has meanwhile achieved respectable levels of commercial success, such as AR advertising.
- Snapchat – the biggest beneficiary of mobile AR – even signals that it's an evolutionary step towards glasses.

- **AR glasses have already arrived meaningfully if considering their deployment in enterprise settings.**
- AR glasses' stylistic and wearability challenges aren't prevalent in the workplace, where sensibilities differ.
- There are also clearer ROI and business cases for enterprise AR, including productivity enhancements.
- Consumer AR glasses spending will eventually eclipse that of enterprises due to larger population sizes.
- That process will take several years to unfold, following common tech patterns of early-stage enterprise adoption.

- **ARtillery projects AR glasses revenue to grow from $822 million in 2019 to $13.4 billion in 2024.**
- Enterprise spending represents 98 percent of that total today, retracting to 90 percent by 2024.
- This is steep growth, as it starts with a small base and will be accelerated by an enterprise tipping point in 2022.
- Consumer spending growth will be accelerated by Apple's projected market entrance, also in the 2022 timeframe.

- **Apple's market entrance will lead to meaningful device sales for its own glasses and others (halo effect).**
- Though it will be the market leader, Apple's AR glasses will sell less than 5-million units in their first three years.
- This projection factors in historical growth for emerging and category-defining products like iPhone and Watch.
- Though growth will be steep, aggregate AR glasses sales in 2024 will be dwarfed by smartphone sales 2000 to 1.

- **As for smart glasses themselves, they could defy – or at least broaden – connotations with "AR."**
- Apple only aims for massive markets, meaning its AR glasses could align with sunglasses or corrective eyewear.
- This reality informs its feature set, possibly including HDR digital filters that improve or enhance human vision.
- Its glasses could also facilitate utilities such as local commerce (see project Gobi[viii]) and iOS notifications.
- It could also achieve sensor fusion with other wearables (AirPods and Watch) for holistic sensory augmentation.

- **Apple's V1 glasses could be described as "AR lite," evolving over several generations (like the iPhone).**
- Underlying optical and display technologies dictate that visual intensity and sleekness are mutually exclusive.
- Given this choice, Apple will opt for the former as it aligns with both its design sensibilities and larger markets.
- This will shift the industry's attention towards *wearability* as a core design principle for smart glasses.

- **Rather than graphically-rich glasses that get sleeker over time, the reverse evolutionary path will prevail.**
- This flips the model that prioritized graphical UX over hardware style and wearability (see Magic Leap).
- With the *wearability* principle in mind, technologies further down the stack will adjust to this target.
- This will include all parts of the AR value chain including optical technologies and display systems.

- **Speaking of the underlying tech stack, a largely under-appreciated set of technical barriers looms.**
- Primary components are optical and display systems, which have a direct impact on glasses quality and comfort.
- Quality refers to UX factors like brightness, field of view, and resolution, which represent sizeable challenges.
- Comfort refers to physical and social comfort, both requiring smaller glasses that defy needs of the optical system.
- Several technical approaches are being developed, each involving big tradeoffs (detailed later in this report).

- **These technical and practical barriers deviate from generalist media that paints a "blue sky" picture.**
- Though well-intentioned, this sets AR up to fail commercially by setting overblown consumer expectations.
- A "reset" is required for the consumer view on realistic AR glasses that will arrive soon from Apple and others.
- That reset is already underway, considering the market correction from AR's circa-2017 hype cycle.
- Accurate expectations will ensure appreciation for the steps and milestones in AR's evolutionary journey.

# About ARtillery Intelligence

**ARtillery Intelligence** chronicles the evolution of spatial computing. Through writings and multimedia, it provides deep and analytical views into the industry’s biggest players, opportunities and strategies.

Run by analysts and former journalists, coverage is grounded in a disciplined and journalistic approach. It also maintains a business angle: Though there are lots of fun and games in spatial computing, cultural, technological and financial implications are the primary focus.

Products include the **AR Insider** publication and the **ARtillery PRO** research subscription, which together engender a circular flow of knowledge. Research includes monthly narrative reports, market-sizing forecasts consumer survey data and multi-media, all housed in a robust intelligence vault.

Learn more **here**.

# About Intelligence Briefings

ARtillery Intelligence Briefings are monthly installments of spatial computing analysis. They synthesize original data to reveal opportunities and dynamics of spatial computing sectors. A layer of insights is applied to translate market events and raw figures into prescriptive advice.

More information, past reports and editorial calendar can be seen **here.**

# About the Author

Mike Boland was one of Silicon Valley's first tech reporters of the Internet age, as a staff reporter for *Forbes* (print) starting in 2000. He has been an industry analyst covering mobile and social media since 2005, and is now Chief Analyst of ARtillery Intelligence and Editor-in-Chief of *AR Insider.*

Mike is a frequent speaker at industry conferences such as AWE, VRLA and XRDC. He has authored more than 120 reports and market-sizing forecasts on the tech & media landscape. He contributes regularly to news sources such as *TechCrunch*, *Business Insider* and the *Huffington Post*.

A trusted source for tech journalists, his comments have appeared in A-list publications, including *The New Yorker*, *The Wall Street Journal* and *The New York Times*.

Further background, history and credentials can be read **here.**

# Methodology

This report highlights ARtillery Intelligence viewpoints, gathered from its daily in-depth coverage of spatial computing. To support narratives, data are cited throughout the report. These include ARtillery Intelligence original data, as well as that of third parties. Data sources are attributed in each case.

For market sizing and forecasting, ARtillery Intelligence follows disciplined best practices, developed and reinforced through its principles' 15 years in tech-sector research and intelligence. This includes the past 5 years covering AR & VR exclusively, as seen in research reports and daily reporting.

Furthermore, this report includes guest commentary. **Ostendo** VP of visual experience and **the AR Show** host Jason McDowall contributed insights on AR glasses technical hurdles. More on ARtillery Intelligence market-sizing research and methodologies can be read **here.**

# Disclosure and Ethics Policy

ARtillery Intelligence has no financial stake in the companies mentioned in this report, nor was it commissioned to produce it. With respect to market sizing, ARtillery Intelligence remains independent of players and practitioners in the sectors it covers, thus mitigating bias in industry revenue calculations and projections.

ARtillery Intelligence's disclosure and ethics policy can be seen in full **here.**

# Contact

Questions and requests for deeper analysis can be submitted **here.**

# Reference

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[i] ARtillery Intelligence Report, **Mobile AR Revenue Forecast, 2019-2024** (sign-in required)
[ii] ARtillery Intelligence Article, **Triangulating Clues in Apple's AR Roadmap** (sign-in required)
[iii] ARtillery Intelligence Report, **AR Advertising Deep Dive, Part I: Case Studies** (sign-in required)
[iv] ARtillery Intelligence Report, **Wearables: Paving the Way for AR Glasses** (sign-in required)
[v] ARtillery Intelligence Article, **Triangulating Clues in Apple's AR Roadmap** (sign-in required)
[vi] ARtillery Intelligence Article, **Will AR Enable Retail's Touchless Era?** (sign-in required)
[vii] ARtillery Intelligence has a **media partnership** with the AR Show but no money changes hands.
[viii] ARtillery Intelligence Article, **Triangulating Clues in Apple's AR Roadmap** (sign-in required)

Cover Image source: **Morning Brew**